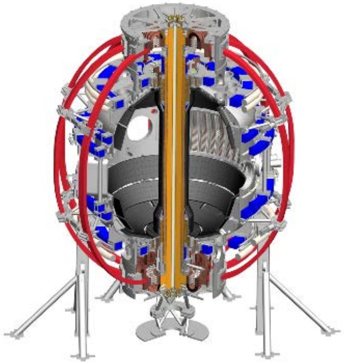
NSTX-U Research Plans for FY2016-18

J. Menard, M. Ono - PPPL

For the NSTX-U Research Team

FY2018 FES Budget Planning Meeting
Germantown, MD
April 13, 2016



NSTX-U research benefits greatly from highly collaborative program

Domestic (33)

- College of William and Mary
- Columbia University
- CompX
- Florida International Univ.
- General Atomics
- Idaho National Laboratory
- Johns Hopkins University
- Lawrence Livermore Nat. Lab.
- Lehigh University
- Lodestar Research Corporation
- Los Alamos National Laboratory
- Massachusetts Institute of Tech.
- Nova Photonics, Inc
- Oak Ridge National Laboratory
- Old Dominion University
- Princeton Plasma Physics Lab
- Princeton University
- Purdue University
- Sandia National Laboratory
- Tech-X Corporation
- U. of California - Davis
- U. of California - Irvine
- U. of California - Los Angeles
- U. of California - San Diego
- U. of California - Space Sci. Lab.
- University of Colorado
- University of Illinois
- University of Maryland
- University of Rochester
- University of Tennessee
- University of Texas
- University of Washington
- University of Wisconsin

402 team members

39 university faculty

21 post-docs

20 grad-students

356 data users

55 institutions

22 US Universities

International (22)

- ASIPP
- CCFE
- FOM Institute DIFFER
- Hiroshima University
- Inst. for Nuclear Research
- IPP-Czech Republic
- Ioffe Physical-Tech. Inst.
- JAEA
- KAIST
- Kyoto University
- Kyushu University
- NFRI
- NIFS
- Niigata University
- Seoul National University
- Tokamak Energy, LTD
- TRINITI
- UNIST
- University of Costa Rica
- University of Hyogo
- University of Tokyo
- University of York

Outline

- NSTX highlight overview, NSTX-U run progress
- NSTX-U mission, priorities, FY16-18 overview
- FY16-18 research plans
- Milestone summary
- ITPA contributions
- ST-FNSF / Pilot Plant study highlights
- Summary

NSTX-U research plan well aligned with
2015 Community Workshop Reports and FES 10-year Plan

NSTX-U Research Team Has Been Scientifically Productive

Very Active in Scientific Conferences, Publications, and Collaborations

- Strong APS meeting participation
  - 2014: 1 ST review talk, 5 NSTX invited talks, 44 posters
  - 2015: 3 NSTX invited talks, 54 posters
- L. Delgado-Aparicio: DOE Early Career Award for research on impurity transport and control

- Multitude of technical NSTX-U / next-step presentations at 2015 SOFE, Li Symposium, IAEA-TM on divertors
- International ST Workshop: 78 talks+posters, 50% international
- 45 refereed publications for FY2015
- 34 IAEA FEC 2016 synopses on NSTX-U + ST-FNSF

NSTX-U Research Team Has Been Scientifically Productive

Very Active in Scientific Conferences, Publications, and Collaborations

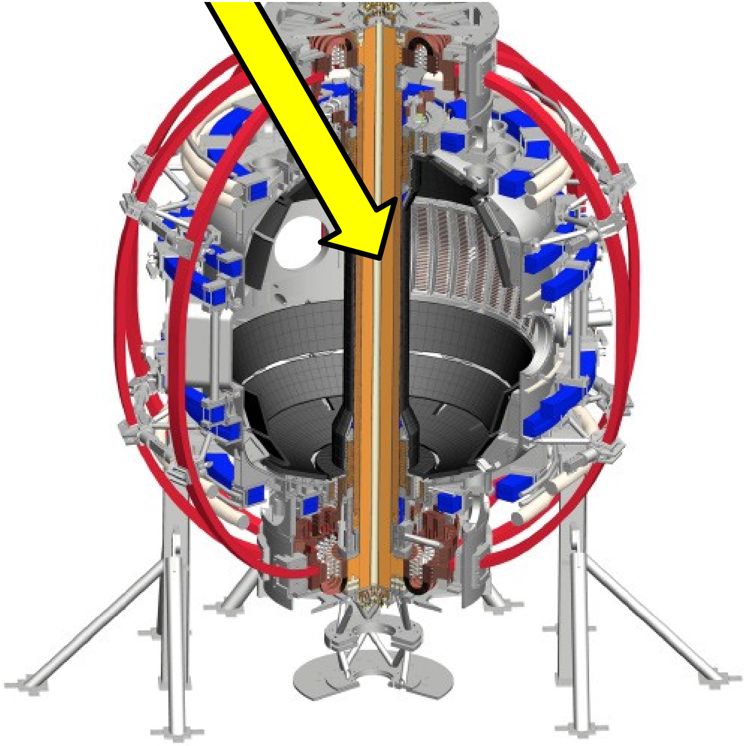
- Collaborative research contributions made in range of topics directly relevant to NSTX-U program
  - **DIII-D:** Pedestal transport, fast-ions instabilities, RWM / RFA, QH-mode TEM particle transport, Li dropper, granule injector, snowflake/X divertors
  - **EAST:** Lithium coating / wall physics, flowing liquid Li limiter
  - **KSTAR:** NTV rotation damping, error fields, RMP
  - **C-Mod:** ELM cycle / pedestal structure, high-Z spectroscopy
  - **MAST / York:** Momentum transport studies / SAMI diagnostic
  - **QUEST:** CHI + ECH start-up research, EBW-CD start-up modelling (new)
  - **ITPA** halo current data / studies including DIII-D, AUG, C-Mod, NSTX

Propose to enhance collaboration with MAST-U, especially in boundary area

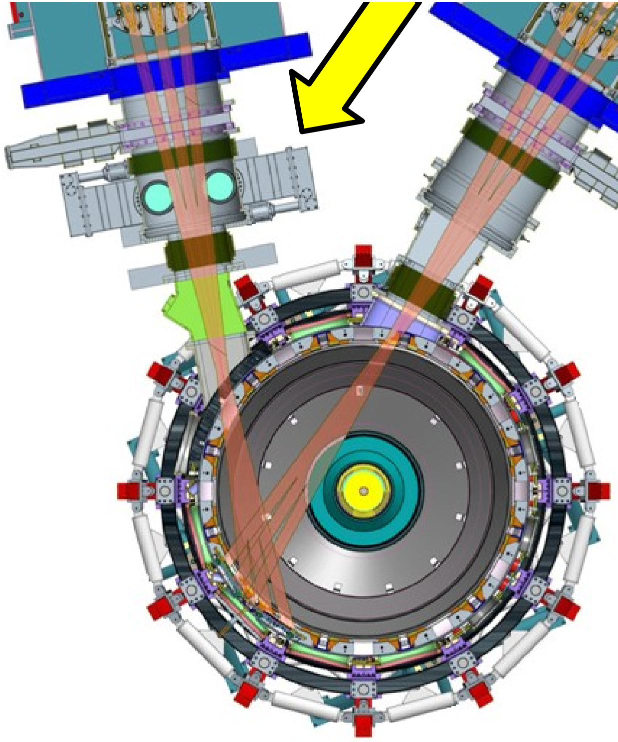
- MAST-U construction nearing completion
  - Late CY16 pump-down, commissioning, mid-CY17 plasmas
- Opportunity to engage with MAST-U boundary program to complement NSTX-U by scoping exhaust solutions
  - Comparison of divertor geometry (Super-X, snowflake, std.)
  - Enhance MAST-U radiation diagnostics, leveraging NSTX-U
    - ORNL-led (M.L. Reinke) w/ contributions from PPPL
  - NSTX-U provides info on high-Z PFCs / impurity transport, liquid metals
- Continue to grow links between ST programs and cover a wider range of science + engineering activities
  - Increase MAST-U/UK research participation in NSTX-U (FY16-18)
  - Develop and utilize remote collaboration capabilities / control room
  - Assess facility enhancements
    - MAST-U 3D field capabilities to help inform NSTX-U 3D coil / NCC design choices
  - Continue joint work on ST FNSF / Pilot concepts

NSTX-U will access new physics with 2 major new tools:

1. New Central Magnet



2. Tangential 2nd Neutral Beam



<u>Higher T, low ν^* from low to high β</u>

→ Unique regime, study new transport and stability physics

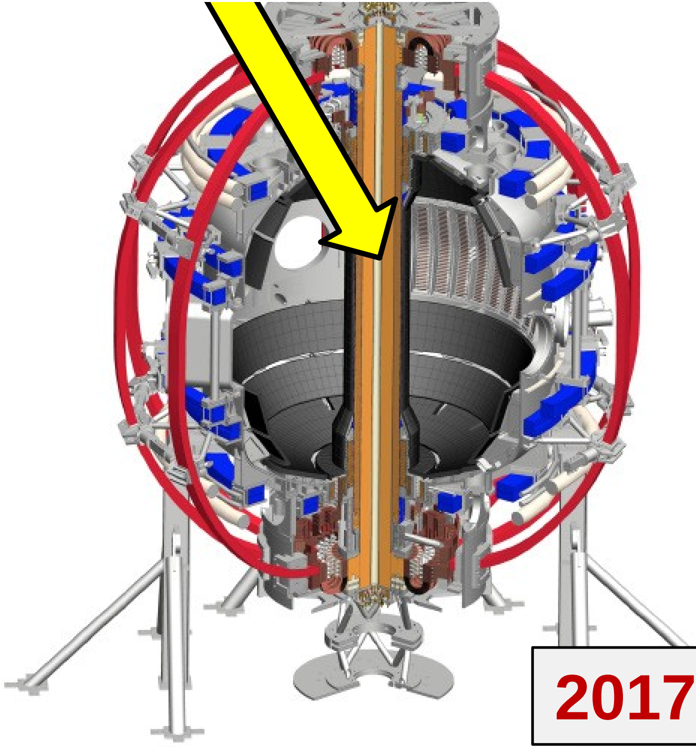
<u>Full non-inductive current drive</u>

→ Not demonstrated in ST at high-β_T

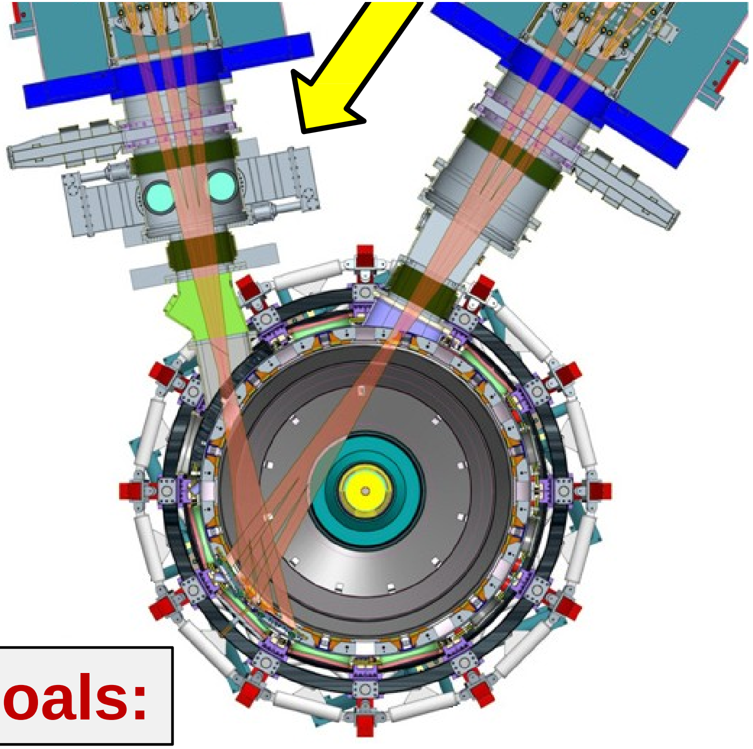
Essential for any future steady-state ST

NSTX-U will have major boost in performance

1. New Central Magnet



2. Tangential 2nd Neutral Beam



2017-2018 goals:

- 2× toroidal field (0.5 → 1T)
- 2× plasma current (1 → 2MA)
- 5× longer pulse (1 → 5s)

- 2× heating power (5 → 10MW)
  - Tangential NBI → 2× current drive efficiency
- 4× divertor heat flux (→ ITER levels)
- Up to 10× higher $nT\tau_E$ (~MJ plasmas)

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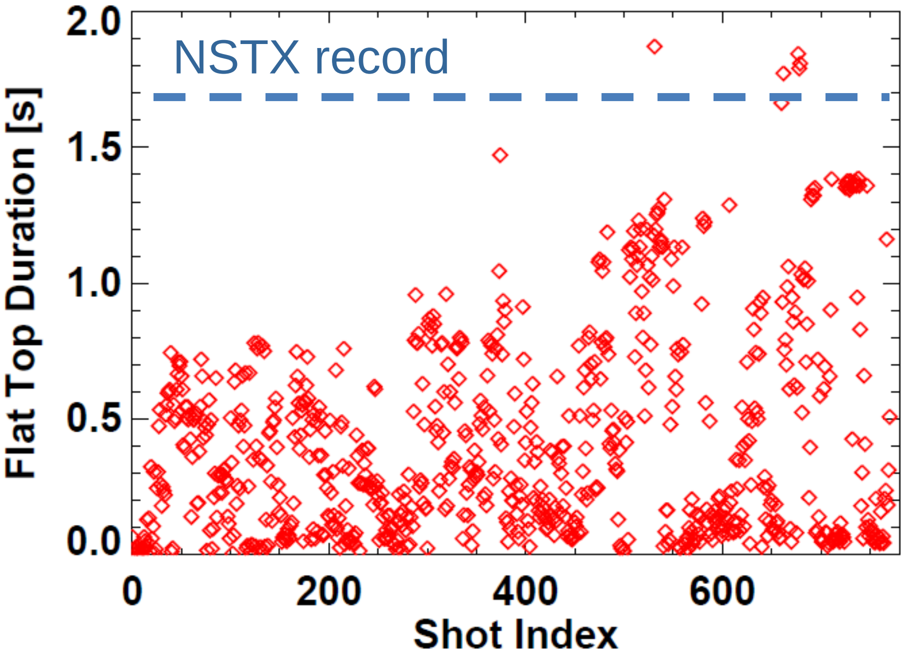
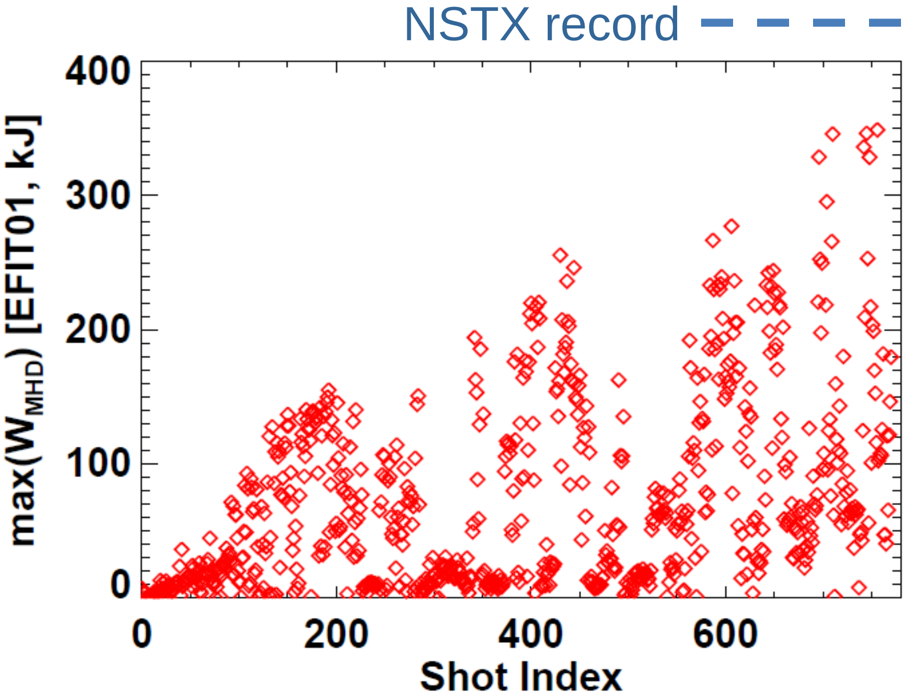
NSTX-U plasma commissioning status

- ~7 run weeks of ops, I_P = 0.5–1MA, boronized PFCs
- Nearly all shots at B_T = 0.6-0.65T > NSTX max = 0.55T
- All 6 NBI injected into plasmas, 4-6MW routinely available

Exceeded NSTX L & H-mode pulse-lengths using 1MW L-modes (0.65, 0.8MA)

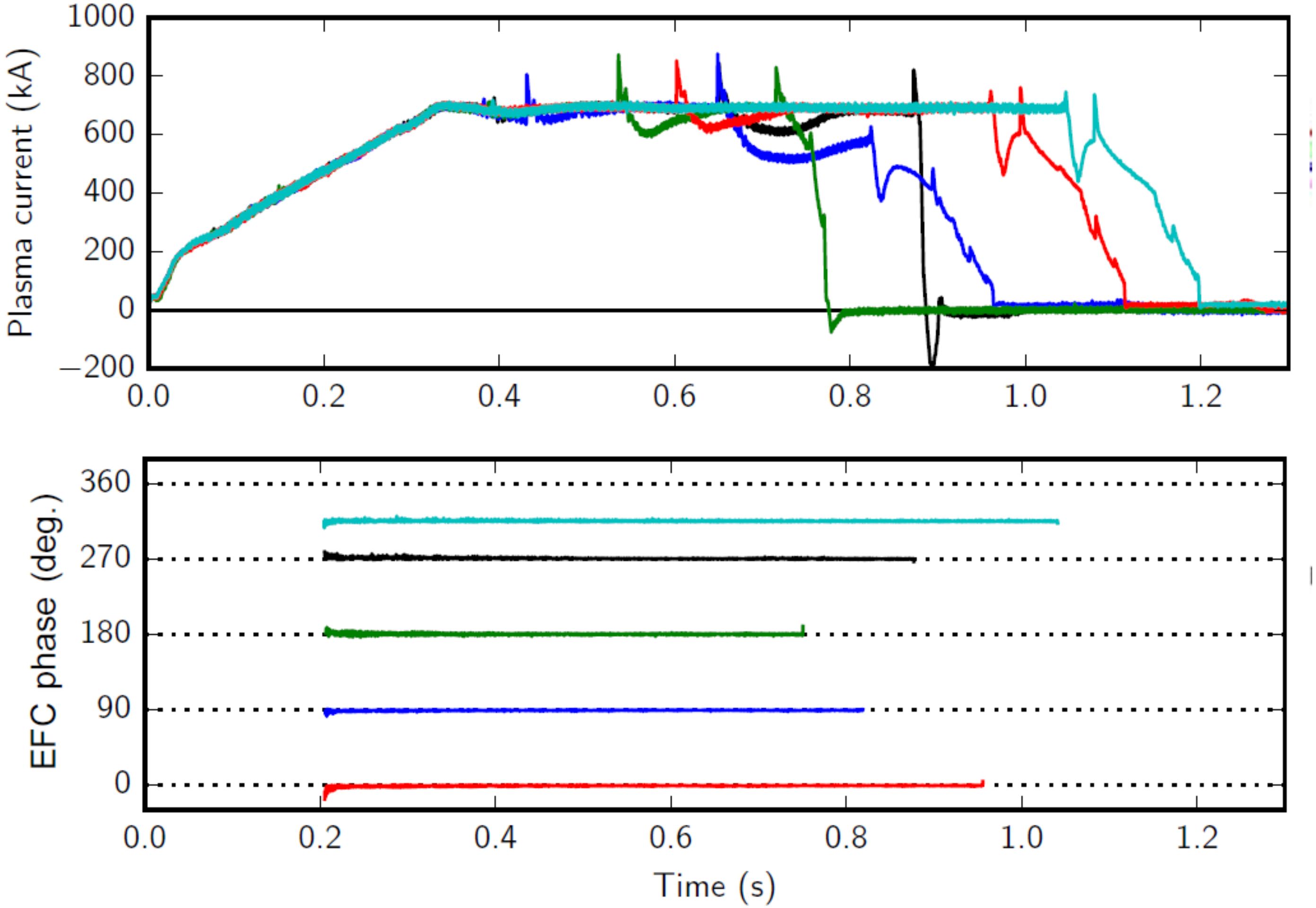


Approaching NSTX W_{TOT} record ~ 430kJ

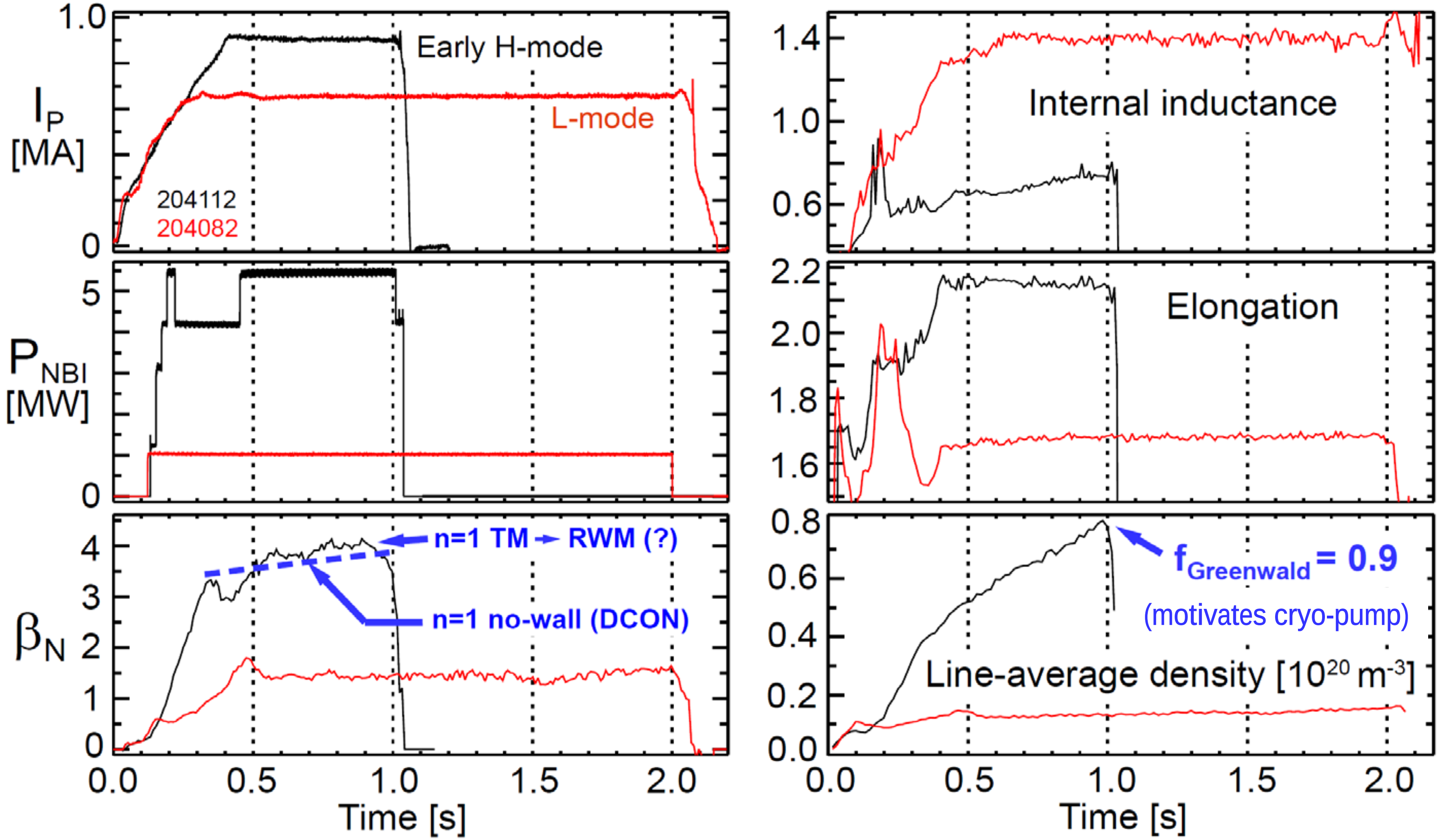


Optimal n=1 error field correction amplitude and phase identified to maximize pulse length, discharge performance

- Dominant error-field source: PF5 vertical field coils
- Long-pulse L-modes used to identify optimal correction amplitude, phase

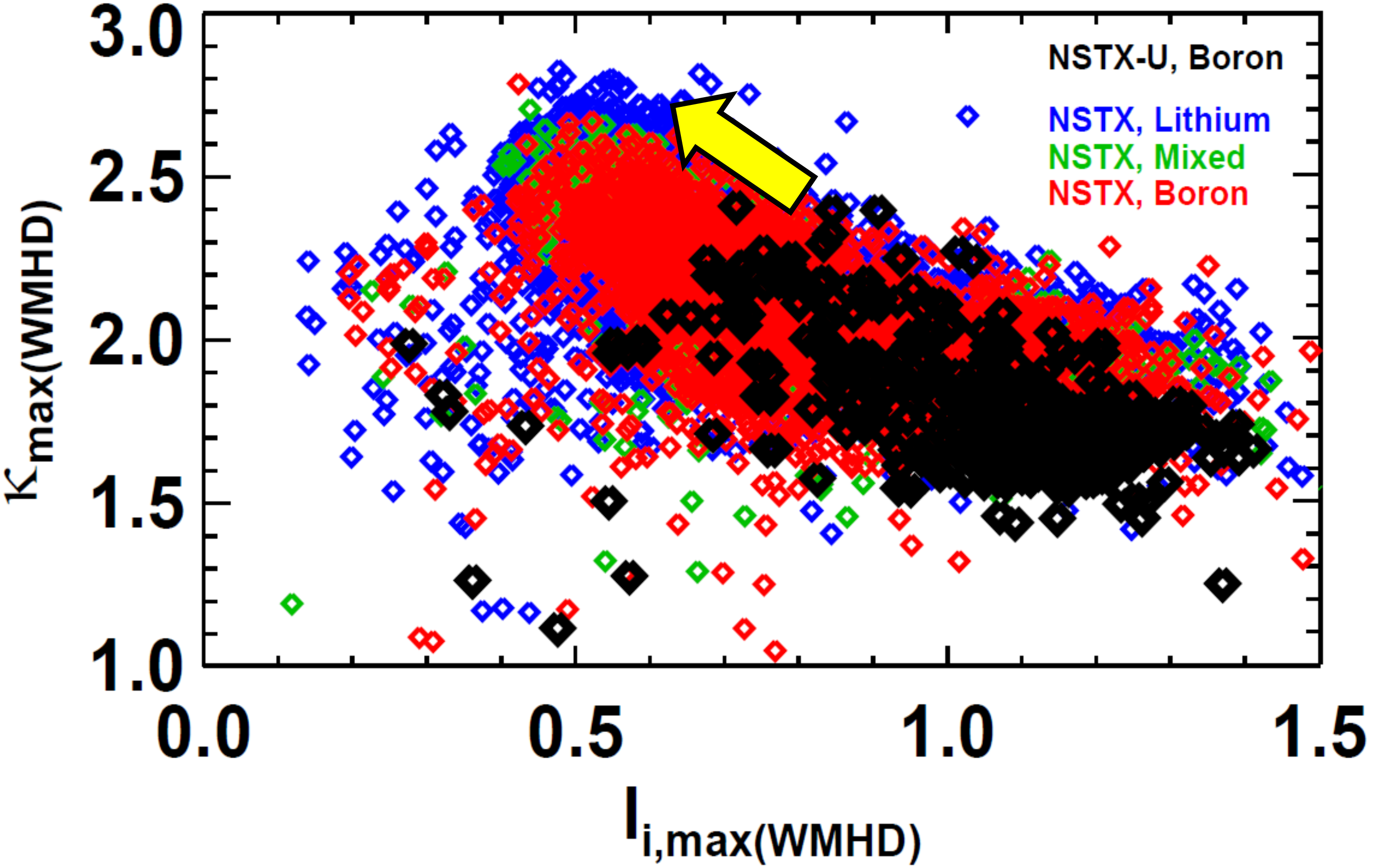


Examples of high-performance L and H-modes achieved thus far



NEXT: Increase κ to avoid tearing, active RWM control, trigger ELMs (ΔR_{sep}, granule injector)

On path to high I_P without tearing modes by elevating q_{min} with early heating + H-mode → l_i=0.5-0.6, κ=2.5-2.7



- Utilizing real-time EFIT / ISOFLUX (GA collaboration)
  – Also utilizing improved vertical motion detection

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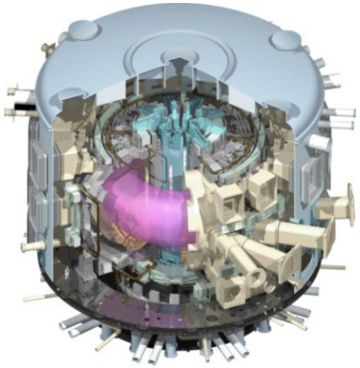
NSTX-U Mission Elements:

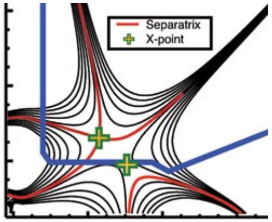
- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond



ITER

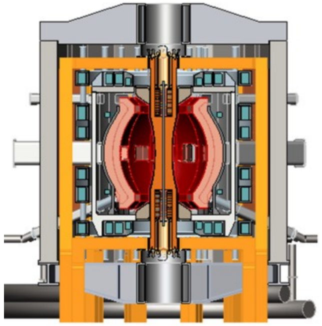
- Develop solutions for plasma-material interface (PMI)

Liquid metals / Lithium

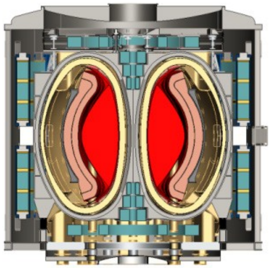


Snowflake/X

- Advance ST as Fusion Nuclear Science Facility and Pilot Plant



ST-FNSF / Pilot-Plant



5 year goal: Establish core physics/scenarios for ST
10 year goal: Integrate high-performance core + metal walls

Next 5 years

Establish ST physics / scenarios:

- Confinement vs. β , collisionality
- Sustain high β with advanced control
- Non-inductive start-up, ramp-up
- Mitigate high heat fluxes
- Test high-Z divertor, Li vapor shielding

Inform choice of FNSF configuration:

- Lower A or higher A?
- Standard, snowflake, Super-X (MAST-U)?

Second 5 years

High-performance + metal walls

- Convert all PFCs from C to high-Z
- Static → flowing Li divertor module(s), full toroidal flowing Li divertor, high T_{wall}
- 5s → 10-20s for PFC/LM equilibration
- Assess ST with high-Z, high-Z + Li

Inform choice of FNSF / DEMO plasma facing materials:

- High-Z consequences? need high-Z + Li?
- Assess for both divertor and first-wall

NSTX-U will address key physics questions during next 3 years leveraging unique capabilities

Establish ST physics / scenarios:

Confinement vs. β , collisionality

Sustain high β w/ advanced control

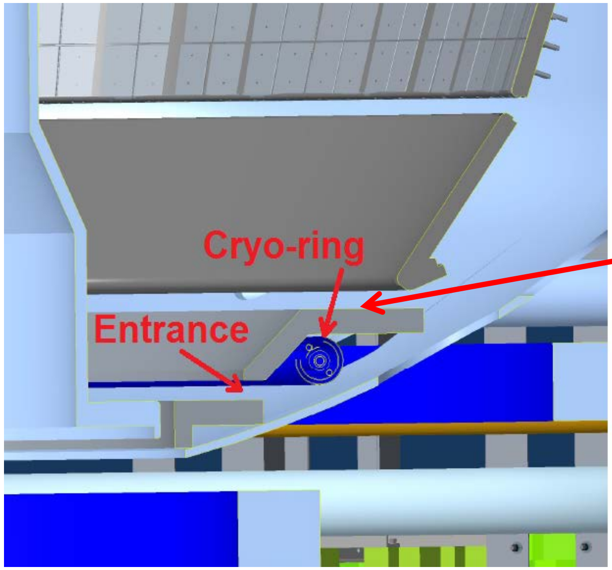
Non-inductive start-up, ramp-up

Mitigate high heat fluxes

Test high-Z divertor, Li vapor shielding

- What role do electromagnetic effects play in electron energy transport? (High β, lower ν^*)
- Can fast-ion instabilities be predicted and controlled for ITER and beyond? (Vary v_f / v_A, β_f, anisotropy)
- Can ST operate near & above no-wall limit and 100% non-inductive?
  - Only ST in world capable of this research critical for steady-state FNSF / Pilot Plant
- What physics determines SOL heat flux width? (Low-A, 2× I_P , Li wall)
- How do advanced divertors and Li impact edge transport, scenarios?

Prioritization of next major facility enhancements



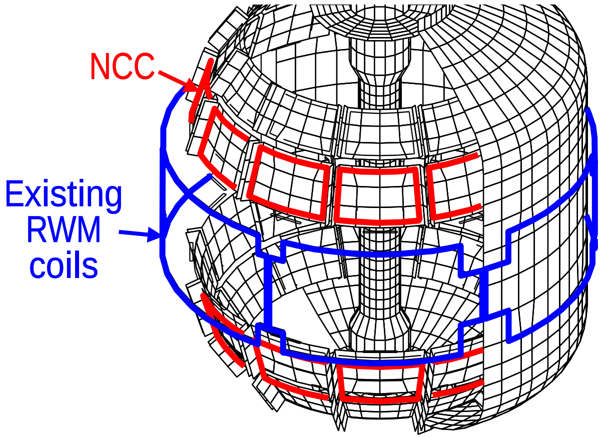
1. Divertor cryo-pump with high-Z baffle
   - Control density and ν^* without Li, compare to Li
   - High-Z cryo-baffle to accelerate transition to high-Z PFCs & support liquid Li/metal research

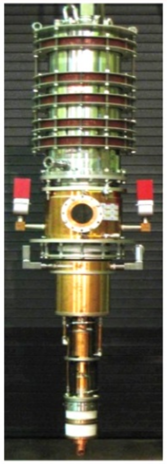
2. Non-axisymmetric control coils (NCC)
   - Resonant, non-resonant NTV rotation control
   - RMP ELM suppression (not yet achieved in ST)
   - Enhanced RWM and EF control

OR

ECH: 28GHz / 1MW gyrotron (Tsukuba)
   - Heat CHI target w/ ECH for HHFW
   - EC/EBW-only CD for start-up
   - Longer-term: EBW CD for sustainment
   - Central e-heating for high-Z expulsion?

Full toroidal NCC array (2 x 12)





- **Completing conceptual designs for above this FY**
- **NCC or ECH require sustained incremental funding**

FY16-18 planned research supports 5 highest priority goals of NSTX-U 5 year plan:

R1#-# → Purple boxes indicate Research milestone year and number in this presentation and FWP

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Understand confinement and stability at high beta and low collisionality
  2. Study energetic particle physics prototypical of burning plasmas
- Develop solutions for PMI challenge
  3. Dissipate high edge heat loads using expanded magnetic fields + radiation
  4. Compare performance of solid vs. liquid metal plasma facing components
- Advance ST as possible FNSF / Pilot Plant
  5. Form and sustain plasma current without transformer for steady-state ST

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FY16-18 planned research supports 5 highest priority goals of NSTX-U 5 year plan:

Core Science
- Macroscopic Stability
- Transport and Turbulence
- Energetic Particles

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Understand confinement and stability at high beta and low collisionality
  2. Study energetic particle physics prototypical of burning plasmas

- Develop solutions for PMI challenge
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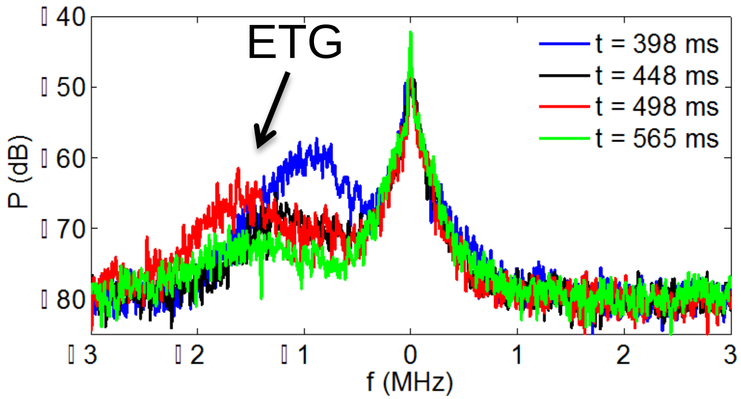
  4. Compare performance of solid vs. liquid metal plasma facing components

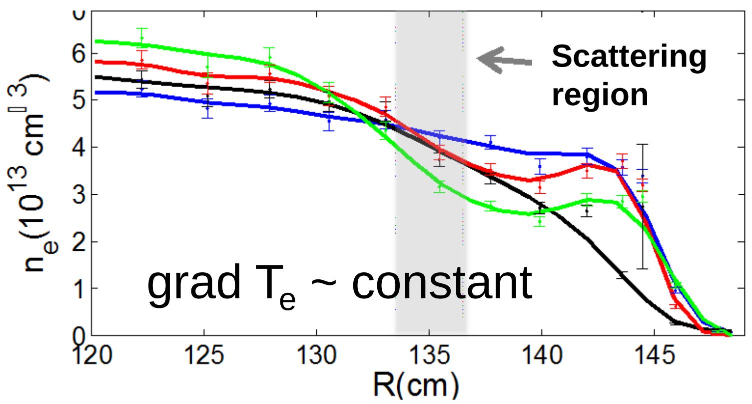
- Advance ST as possible FNSF / Pilot Plant
  5. Form and sustain plasma current without transformer for steady-state ST

NSTX: Linear and non-linear gyrokinetic simulations have shown the role of ∇n_e in stabilizing ETG modes

Decrease in ETG turbulence amplitude with increasing ∇n_e

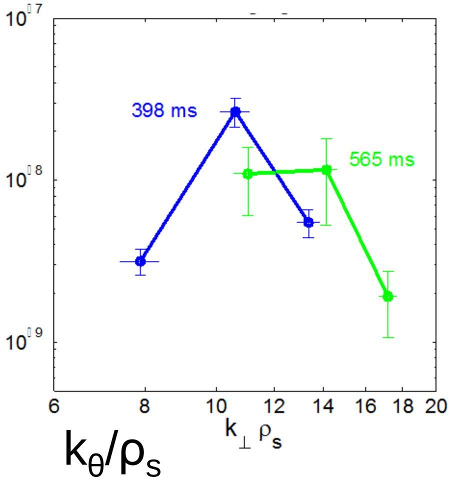
μwave scattering



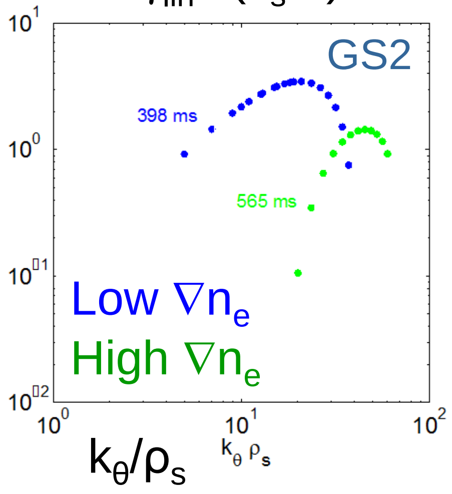


Measured δn/n, linear growth rates, non-linear Q_e all reduced by higher ∇n_e

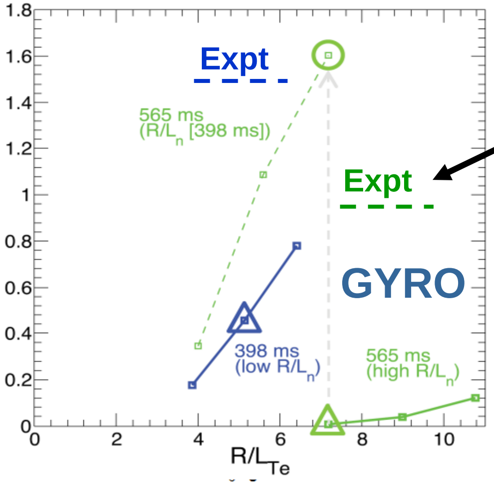
$(\delta n/n)^2$



$\gamma_{lin} / (c_s/a)$



Q_e [MW]



~1MW of e-heat transport from non-ETG?

Ruiz-Ruiz et al.
MIT grad student
PoP (2015)

NSTX: Global non-linear GTS gyrokinetic simulations have identified multiple low-k turbulence transport mechanisms

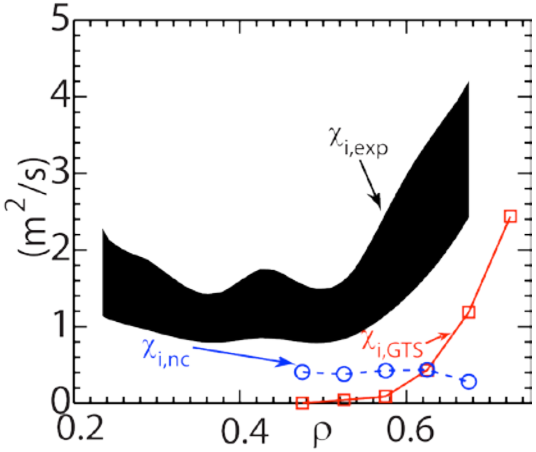
Strong flow shear can destabilize Kelvin-Helmholtz instability

- Non-linear global GTS simulations
- K-H+ITG+Neo ion transport within factor of 2 of expt'l level
- Cannot account for electron transport

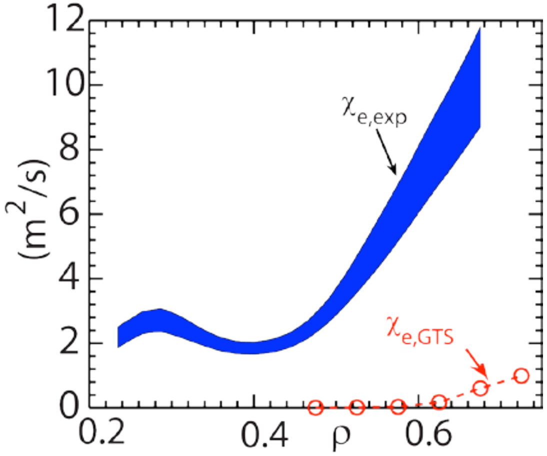
Recent GTS simulations have shown possible role of DTEM in contributing to observed favorable collisionality scaling ($B\tau_{th} \sim \nu_{*e}^{-0.8}$)

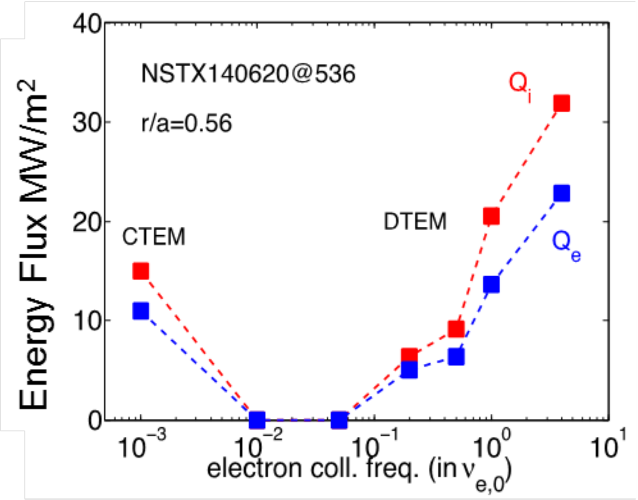
- In addition to microtearing
- Synergy with DIII-D work

Ions



Electrons



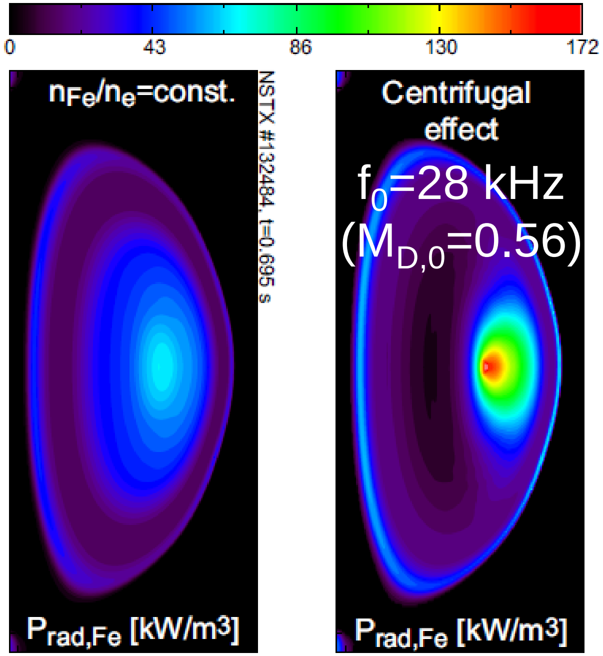


W. Wang et al., NF Letters, PoP (2015)

NSTX-U will study low- and high-Z impurity transport to assess potentially strong rotation effects

- Will investigate if high-Z transport follows neoclassical including centrifugal effects
  - Use 2nd NBI + NTV to vary rotation

$$n_j = n_{j,0} \exp\left(\frac{\frac{1}{2} m_j \omega^2 (R^2 - R_0^2) - eZ_j \Delta\Phi}{k_B T_j}\right)$$



Delgado-Aparicio, HTPD (2014)

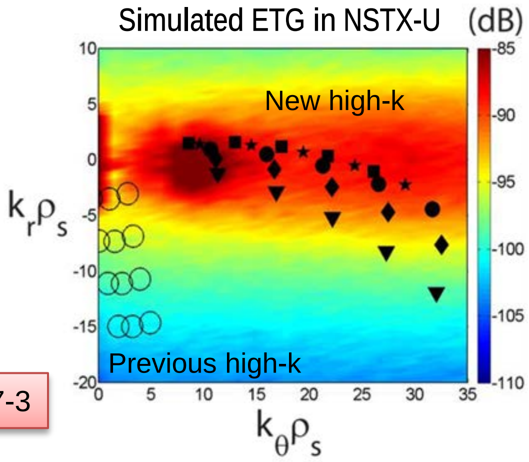
- Investigate particle transport using edge neutral measurement (D_α from MSE, BES; D_β camera) + DEGAS2 calculations
  - Assess perturbative capability using TS, ME-SXR
  - Perturbative particle transport measurements led on MAST in 2013 (Ren)

Collaboration with CCFE

- Impurity transport studies: gas-puff (Ne, Ar), laser blow off (Ca, Mo, W – FY16, LLNL/JHU) and several diagnostic enhancements:
  - Survey x-ray spectrometers (LLNL)
  - XCIS: $V_{\varphi,Z}$, T_Z, n_Z (Ca, Ar, Mo, W) (MIT + PPPL)
  - 1D tangential mid-plane + 2D poloidal bolometers (PPPL + ORNL)

Transport and Turbulence Research Plans for FY2016-18:
First τ_E data at higher B_T, I_P + turbulence, develop reduced χ_e models

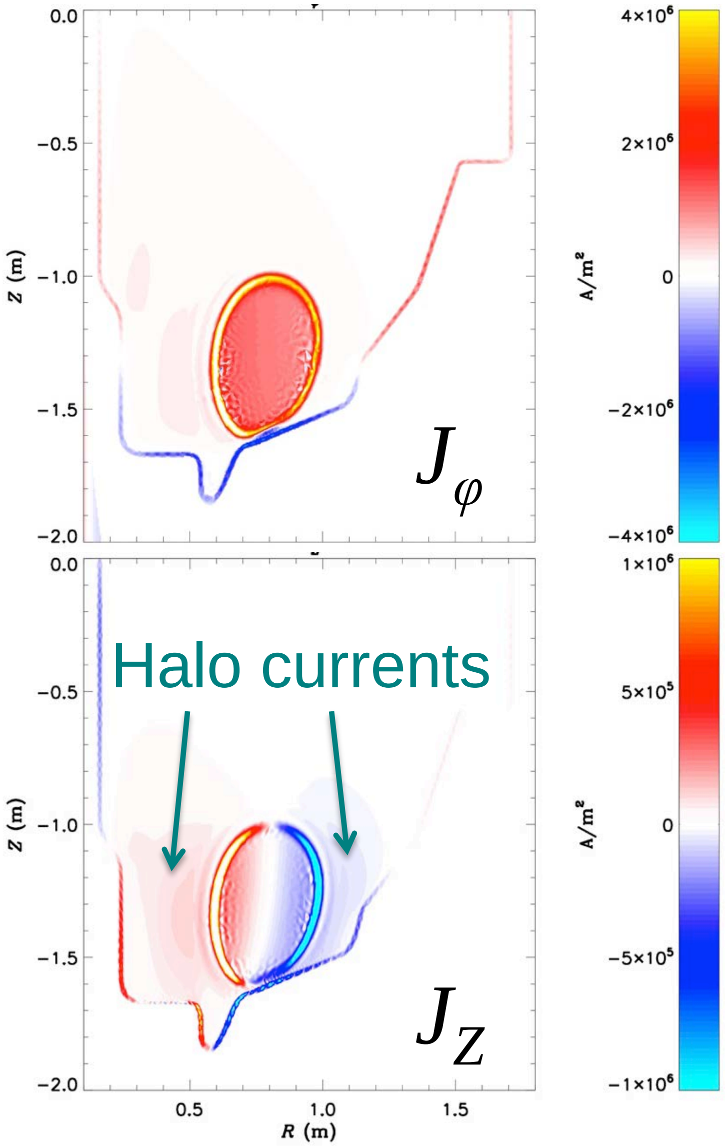
- **FY16**: Extend ST confinement scalings and understanding with up to 60% increase in B_T and I_P R16-1
  - Measure low-k δn (BES w/ increased edge channel count)
- **FY16-17**: Develop and validate reduced transport models using ST data + linear and non-linear gyro-kinetic simulations
- **FY17-18**: Extend confinement studies to full B_T, I_P, 2-3× lower ν*
  - Initial utilization of new high-k FIR scattering system for ETG turbulence
    - Measure k_r & k_θ to study turbulence anisotropy
  - Study turbulence vs. ν*, rotation, q with high-k + BES + cross-polarization-scattering (2018) R17-3



- **FY18**: Assess impurity sources, edge/core impurity transport
  - Utilize new laser blow-off system (LLNL) for edge impurity injection R18-1

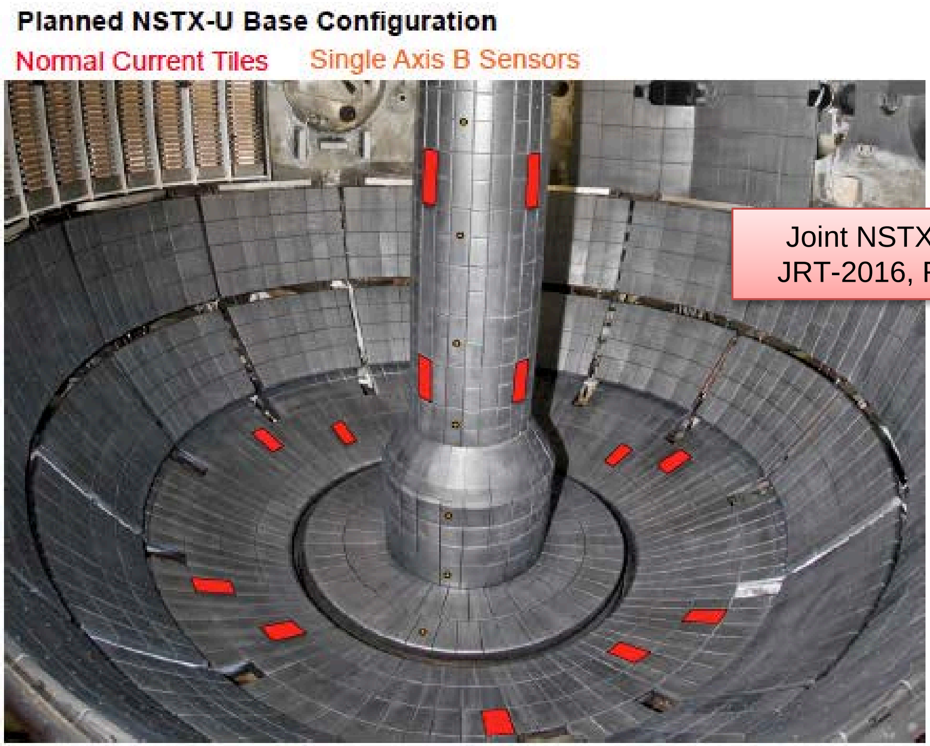
Using advanced simulation capabilities to model disruptions and halo currents for NSTX / NSTX-U

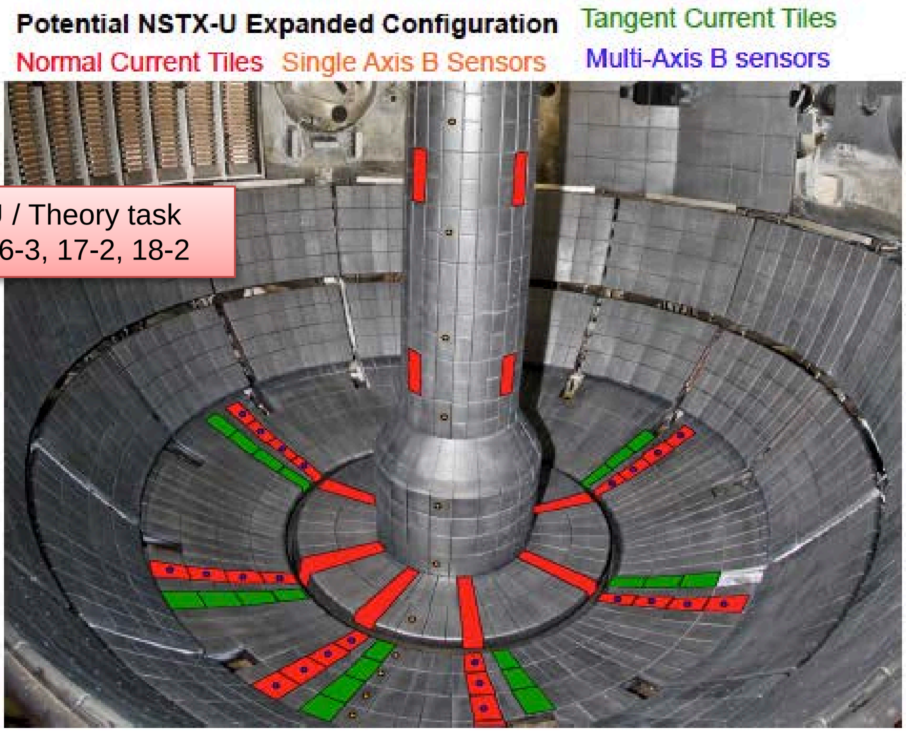
- New resistive wall model in M3D-C1 allows unique capability to simulate mode locking and current-quench
- Includes self-consistent treatment of rotation and halo currents
  - We will seek to validate these models against NSTX-U data



M3D-C^1 with resistive wall capability will be used to map out optimal placement of new B-sensors to study halo currents

- Dynamics of halo currents and forces critical for ITER: particular concern are halo current asymmetries and rotation
- New sensors will measure halo currents, B-fields and JxB forces in NSTX-U
- Critical theoretical issues: (i) role of boundary conditions (ii) halo current distributions in 3D conducting structures (D. Pfefferle – post-doc)


Planned NSTX-U Base Configuration


Potential NSTX-U Expanded Configuration

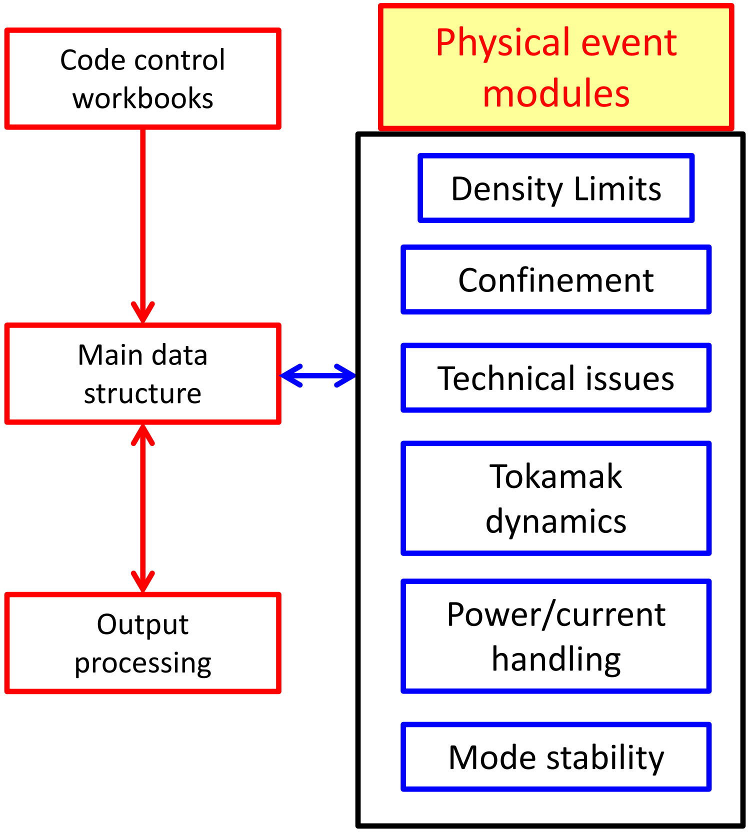
Joint NSTX-U / Theory task
JRT-2016, R16-3, 17-2, 18-2

The DECAF code is being used to characterize disruption event chains on NSTX and NSTX-U, including RWMs

Disruption Event Characterization And Forecasting code

- Structured to ease parallel development
- Module grouping follows deVries
  - BUT, easily appended or altered
- Warning algorithm approach follows Gerhardt
  - BUT, more flexible and extensive

COLUMBIA UNIVERSITY



Code control workbooks

Main data structure

Output processing

Physical event modules

Density Limits

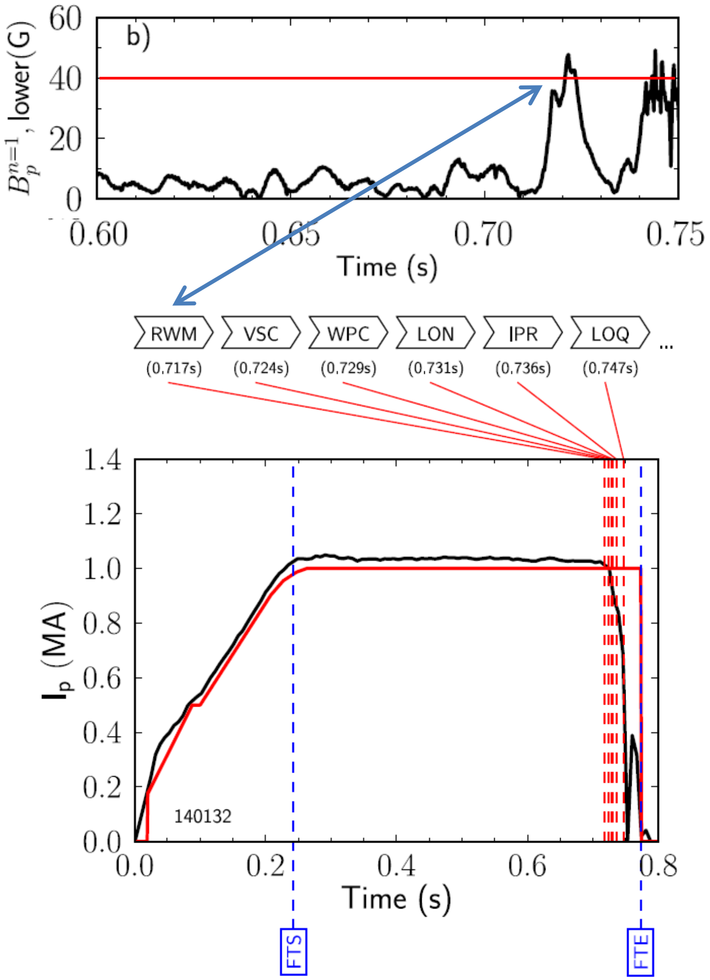
Confinement

Technical issues

Tokamak dynamics

Power/current handling

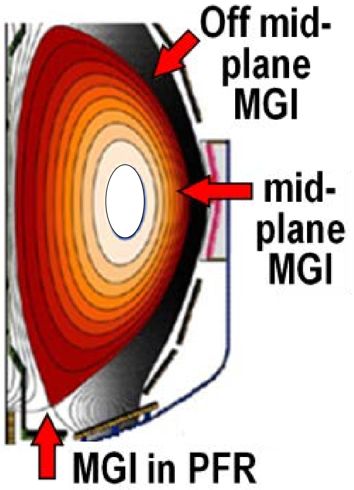
Mode stability



- Disruption event chain
  - Resistive wall mode (RWM) > Vertical stability control (VSC) > … > Disruption
- Longer-term: implement in real-time, link to avoidance/mitigation actuators

Macroscopic Stability Research Plans for FY2016-18:
Complete 3D coil CDR, re-establish high-β ops, assess MGI and halos

- **FY16**: Finalize physics for NCC coil conceptual design
  - Re-establish n=1-3 error-field correction, RWM control, minimize EF rotation damping, sustain operation above no-wall limit R16-3 JRT-2016
  - Test poloidal dependence of Massive Gas Injection (outboard vs. private flux region)

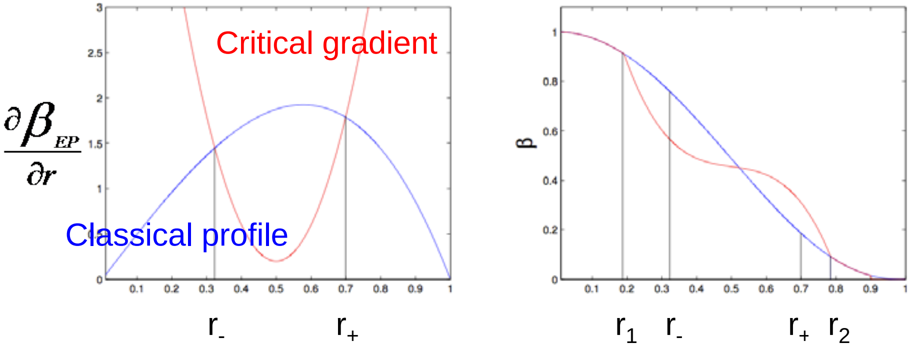


- **FY17**: Contribute unique MGI data (low-A, injector location) for mitigation + warning, prediction
  - Assess mitigation triggering via real-time warning in NSTX-U
  - First data from upgraded halo diagnostics
- **FY18**: Control of current and rotation profiles to improve global stability limits and extend high performance operation R18-2

Models for fast ion profile relaxation in presence of AEs are being validated in-prep for NSTX-U

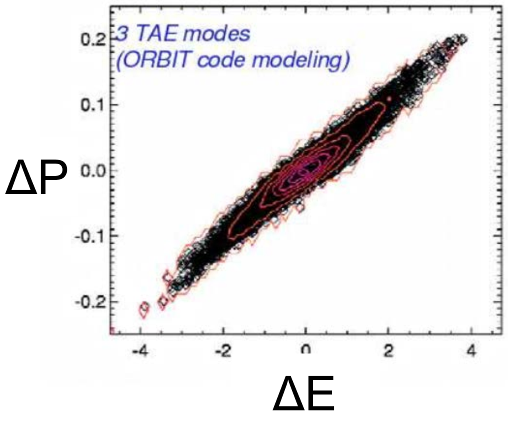
- Critical Gradient Model (Gorelenkov)
  - Compute critical $\partial\beta_{EP}/\partial r$ due to AE
  - Mode growth/damping computed by NOVA-K

Gorelenkov

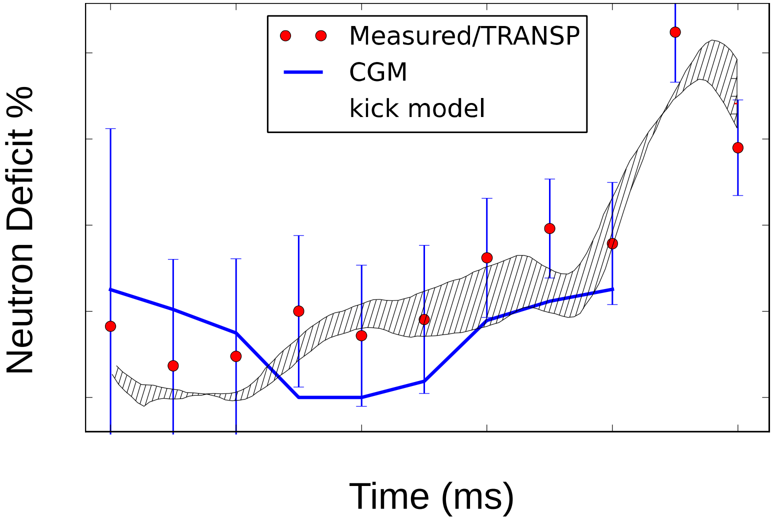


CG used to relax EP profile. It is broadened from the initially unstable one between $r_\pm \rightarrow r_{1,2}$

- "Kick" model (Podesta et al., NF 2015)
  - PDF computed by ORBIT & NOVA
  - Kicks ~ mode amplitude

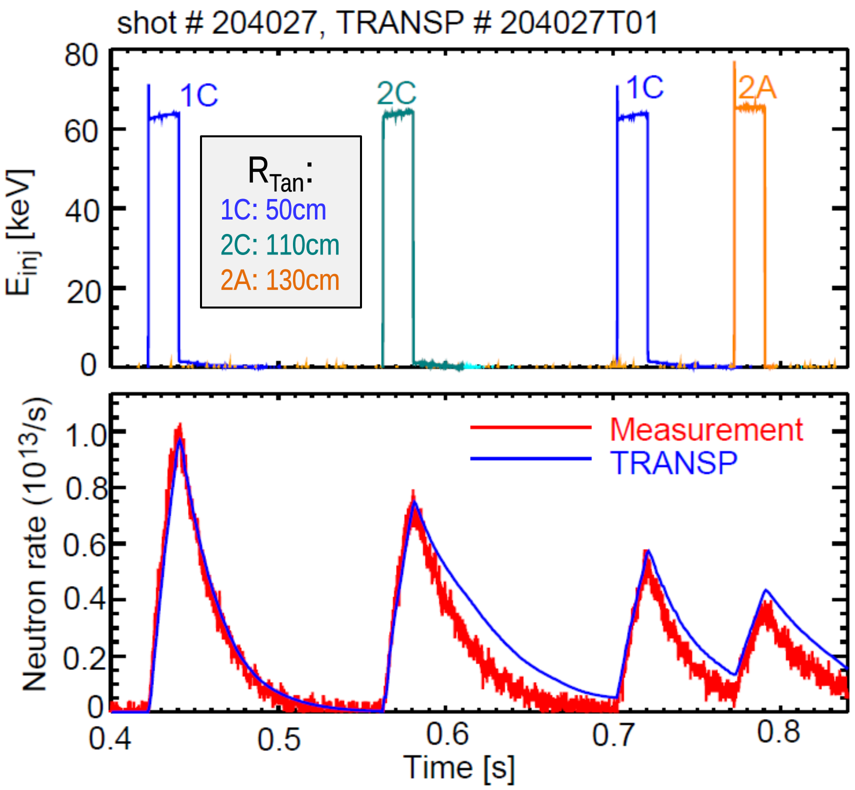


Podesta

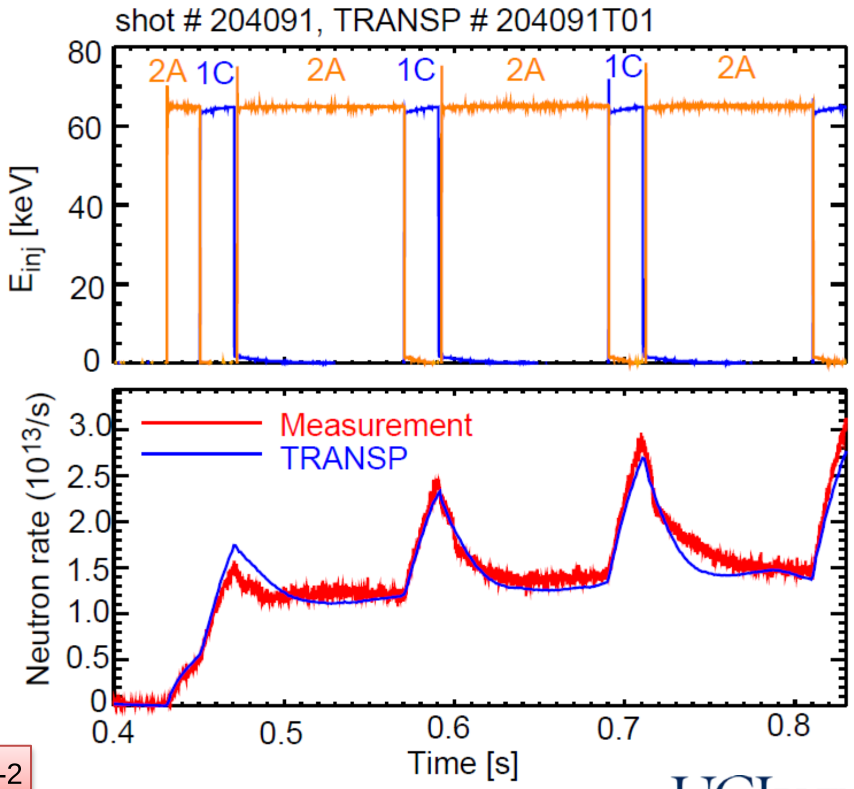


- Both CGM and Kick models reproduce neutron deficit in an NSTX discharge with multiple unstable TAEs
  - Models also being tested on DIII-D (JRT-15)
  - Incorporating both models in TRANSP

New NSTX-U result (preliminary): 2nd NBI fast-ion behavior consistent with classical slowing-down theory



R16-2

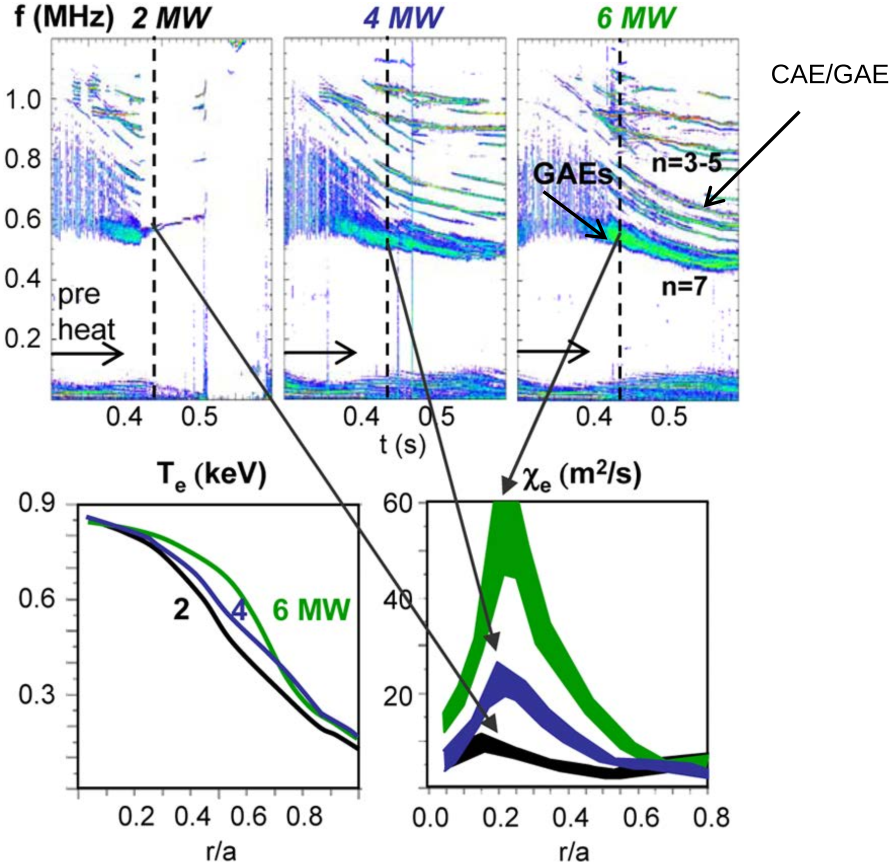


UCIRVINE

- The magnitude, rise and decay rates of neutron signal reasonably agree with the TRANSP prediction which assumes fast ions behave classically
  - Some discrepancy in 2C decay rate → suggest some fast ion loss... due to small sawteeth?

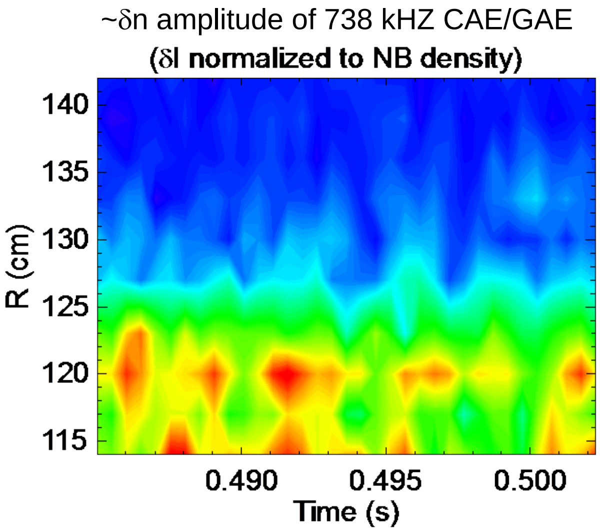
NSTX: Large inferred anomalous core electron transport in presence of CAE/GAEs

- Observation of high frequency Compressional/Global Alfven Eigenmodes (CAE/GAE) modes in plasma core associated with flattening of T_e profile (Stutman, Tritz - JHU)
  - High level of transport (10-100 m^2/s) inferred assuming classical beam physics



Stutman

BES spectra show mode amplitudes peaking from R=115 to 120 cm (r/a~0.2 to 0.3), in region of enhanced transport

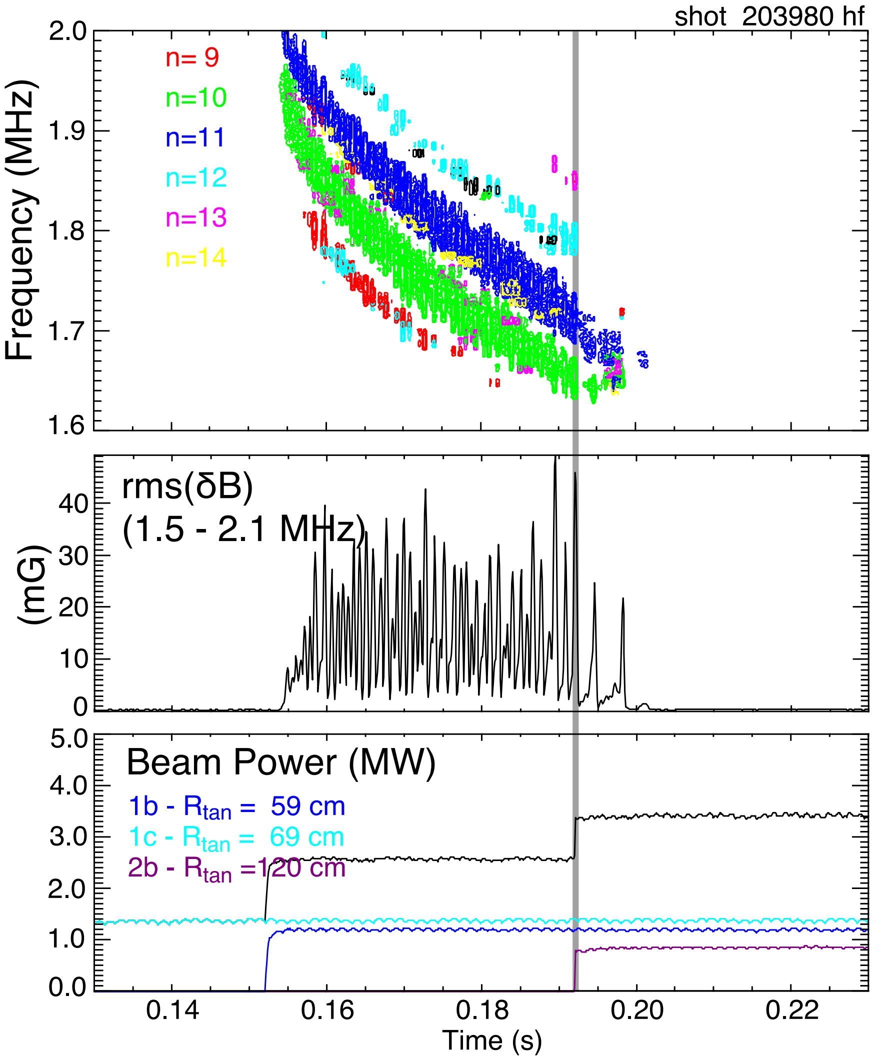


Smith

Is enhanced transport the full picture?

New NSTX-U result: Suppression of counter-propagating GAE observed for large R_{TAN} 2nd NBI

- Top panel:
  - GAE excited by inboard sources 1B / 1C (blue / cyan, lower panel)
- Injection of outboard source 2B starts at 0.192s results in suppression of GAE.
  - Suppression time ~10ms
  - Suppression also with 2A, 2C
- Observations consistent with model of cyclotron-resonant drive of GAE R16-2
- Will investigate whether GAE absence impacts electron thermal transport IR18-2



→ 2nd NBI already powerful new tool for AE physics

Energetic Particle Physics Research Plans for FY2016-18:

Characterize new 2nd NBI, develop full + reduced fast-ion transport models

- **FY16**: Measure fast-ion (FI) density profiles, confinement, current drive, AE stability
  - Exploit new 2nd NBI and higher B_T, access to reduced v_{fast} / v_A R16-2

- **FY17**: Complete model $\chi_{e, AE}$ using measured CAE/GAE mode structures and HYM/ORBIT simulations (w/ T&T group)
  - Does core T_e profile & peaking vary significantly with NBI tangency?
  - Incremental: Assess fast-wave interactions with fast ions at increased field and current IR17-1

- **FY18**: Incremental: Assess role of fast-ion driven instabilities versus micro-turbulence in plasma thermal energy transport
  - Joint between transport and energetic particle groups IR18-2

FY16-18 planned research supports 5 highest priority goals of NSTX-U 5 year plan:

Boundary Science

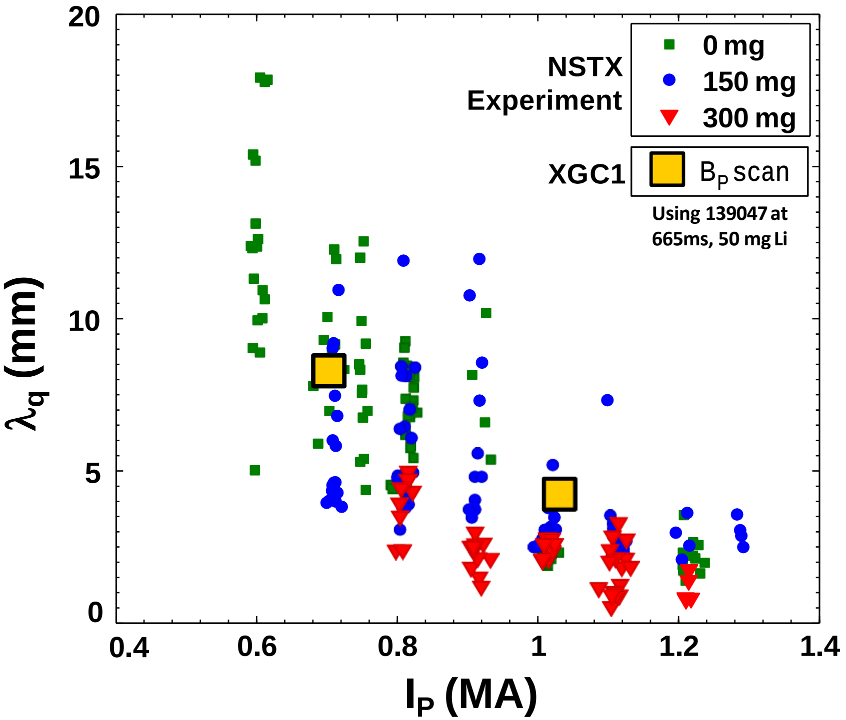
- Pedestal
- Divertor / SOL
- Materials and PFCs

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Understand confinement and stability at high beta and low collisionality
  2. Study energetic particle physics prototypical of burning plasmas
- Develop solutions for PMI challenge
  3. Dissipate high edge heat loads using expanded magnetic fields + radiation
  4. Compare performance of solid vs. liquid metal plasma facing components
- Advance ST as possible FNSF / Pilot Plant
  5. Form and sustain plasma current without transformer for steady-state ST

XGC1 simulations aiding in understanding of SOL heat flux width trends in NSTX

- Experiment shows contraction of SOL heat flux width at midplane with I_p as well as influence of Li conditioning

XGC1 w/ collisions → similar trends



Heat flux width determined primarily by neoclassical processes

XGC-1:

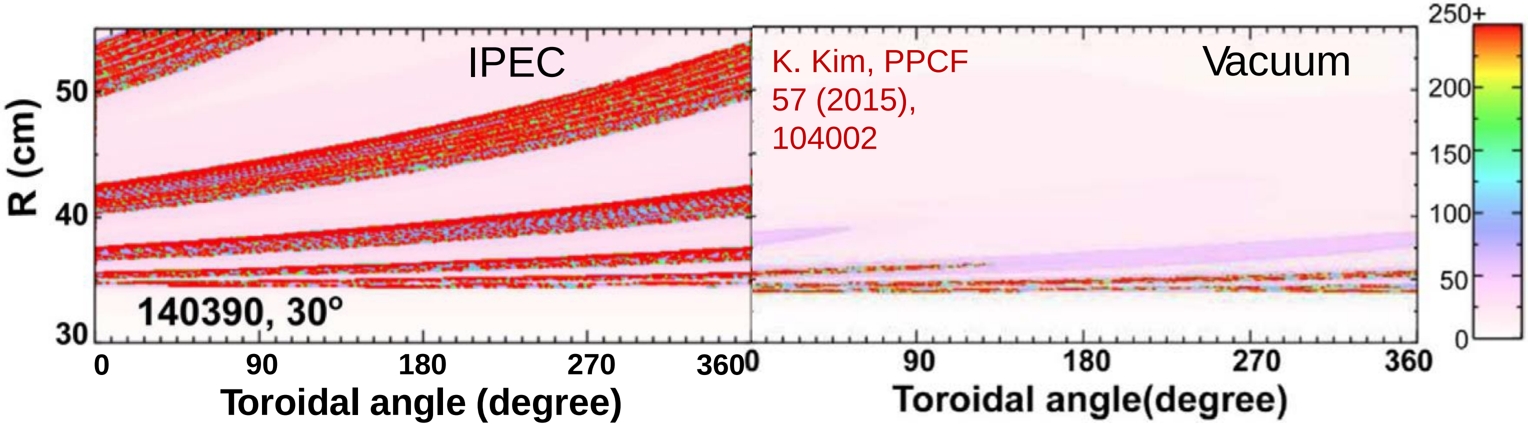
- Full-f, global PIC, kinetic ions, fluid electrons *(kinetic electrons under development)*
- Good candidate for exascale computing initiative

- NSTX data and XGC-1: $\lambda_q \sim 1/I_P^{1.5}$
- How will NSTX-U λ_q scale?
  - Will SOL turbulence become important?

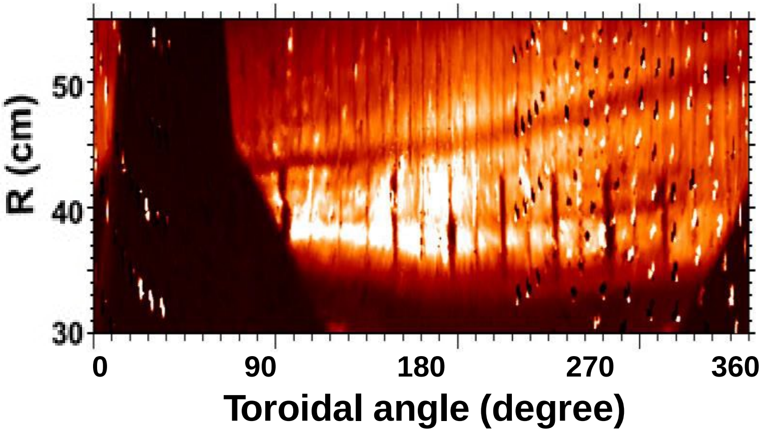
NSTX-U / PPPL
Theory Partnership

Improving understanding of role of plasma response in divertor footprint modification by 3-D fields in NSTX

n=1 perturbation very sensitive to plasma response – amplification of footprint splitting is observed



K. Kim, PPCF 57 (2015), 104002

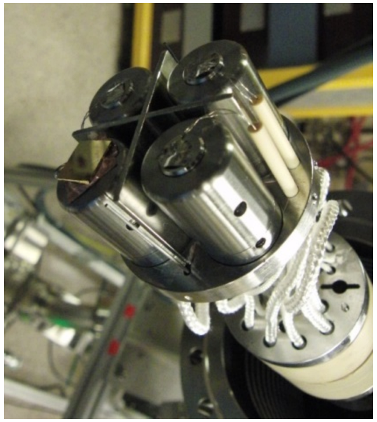


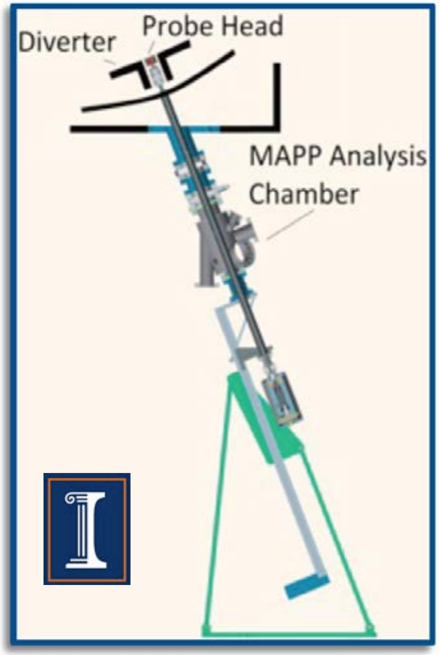
Ideal plasma response substantially amplifies n=1 separatrix splitting → better agreement with IR camera data

- Plasma response effects weaker for n=3 fields (not shown)

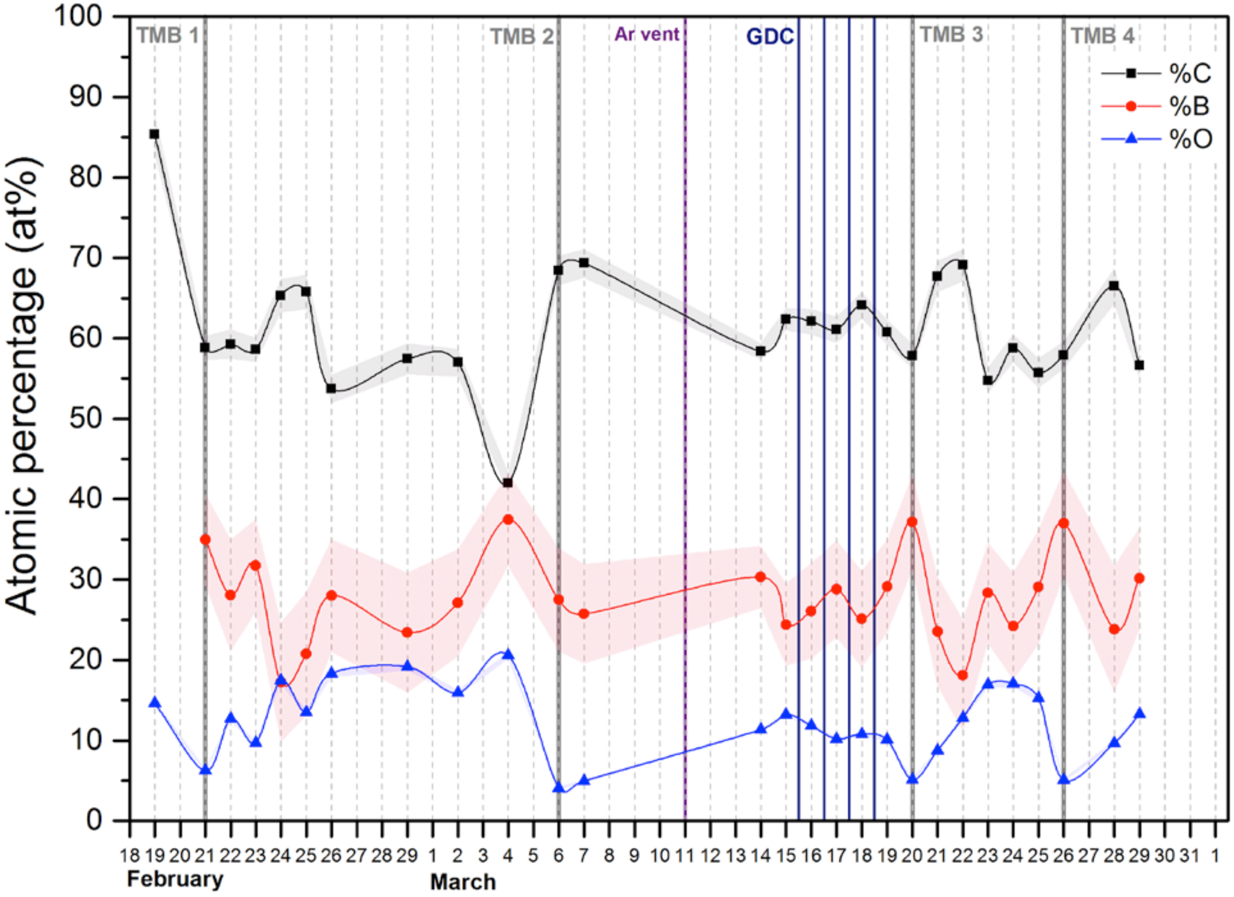
Important for ITER: n=1 EFC + higher-n RMP ELM suppression

Material Analysis & Particle Probe (MAPP) commissioning providing new measurements of surface evolution in NSTX-U





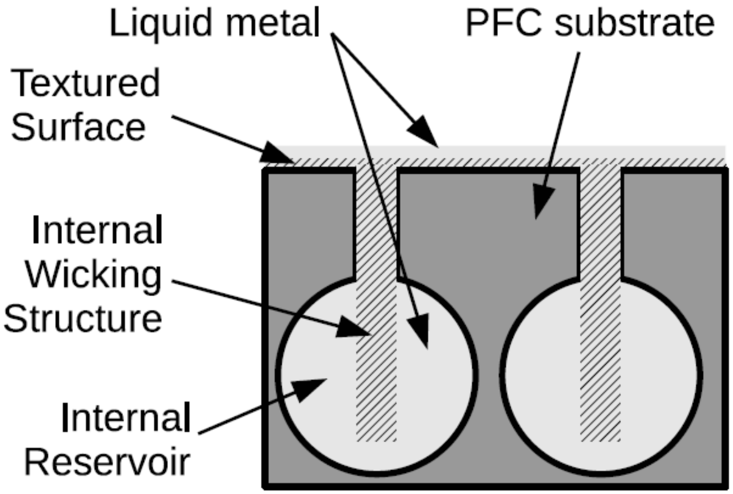
- **Correlating B, O evolution w/ plasma performance**

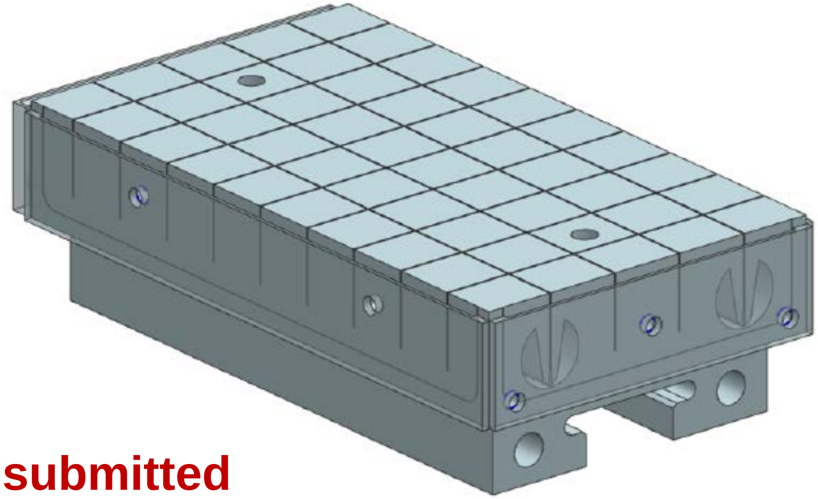


- **Implementing between-shots analysis capability this run**
- **Will help understand complex Li chemistry and evolution**

Developing tiles integrating high-Z substrate with (future) pre-filled Li reservoir to study flowing liquid metal PFCs

- Base high-Z tiles without Li reservoir will be tested during FY17 run
  - Full toroidal row on OB divertor
  - Utilizes wire-EDM fabrication to obtain complex geometry
- Pre-filled Li tile:
  - Similar to capillary porous system (CPS) but applicable as divertor PFC
  - Passive surface replenishment
  - Test in FY2018 (if technically ready)

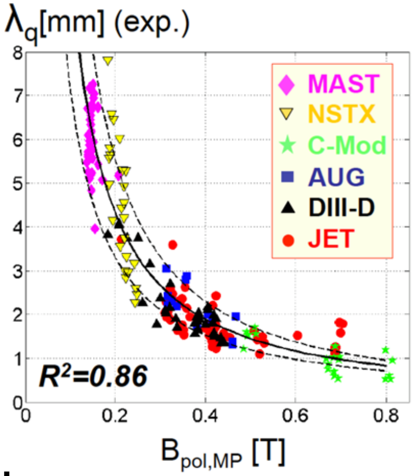




P. Rindt, TU/Eindhoven Thesis, Jaworski FED submitted

Boundary Science Research Plans for FY2016-18

Advance snowflake, cryo, pedestal, SOL studies, extend to higher B_T, I_P



- **FY15**: Measure pedestal structure, SOL width, ELM types, snowflake performance at up to 60% higher I_P, B_T, 2× higher P_{NBI} R16-1
  - Lithium granule injector (LGI) ELM triggering for impurity control, Li coating performance in NSTX-U - compare to EAST/DIII-D results
  - EAST: assess long-pulse particle/impurity control with triggered ELMs, cryo-pumping, lithiumization, high-Z PFCs
- **FY17**: Increase I_P → 2MA → test snowflake, detachment, PFCs with $q_{||}$ up to 4-5× higher than NSTX R17-1
  - Assess high-Z + lithium coated PFC performance with 1 row of high-Z tiles on outboard divertor (at large R) R17-2
- **FY18** (incremental): Investigate power/momentum balance for high density divertor operation (vapor shielding baseline) IR18-1

FY16-18 planned research supports 5 highest priority goals of NSTX-U 5 year plan:

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Understand confinement and stability at high beta and low collisionality
  2. Study energetic particle physics prototypical of burning plasmas
- Develop solutions for PMI challenge
  3. Dissipate high edge heat loads using expanded magnetic fields + radiation
  4. Compare performance of solid vs. liquid metal plasma facing components
- Advance ST as possible FNSF / Pilot Plant
  5. Form and sustain plasma current without transformer for steady-state ST

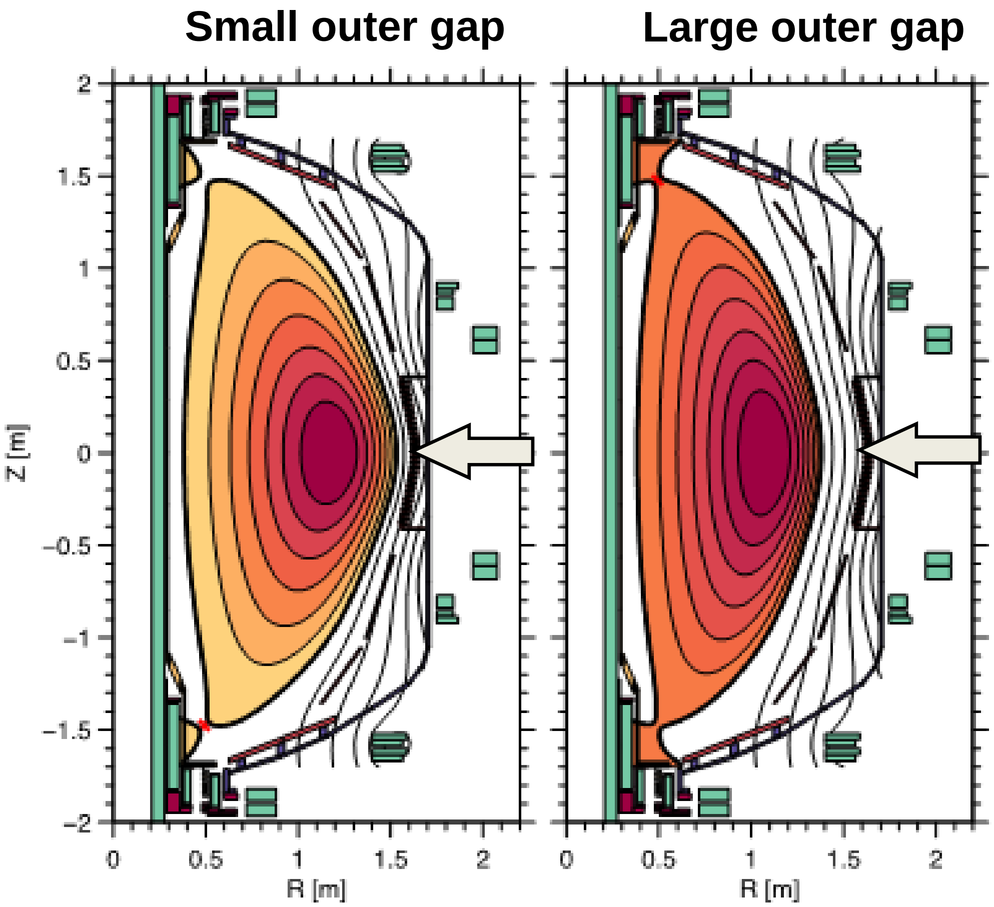
Integrated Scenarios

- Adv. scenarios and control
- Start-up
- Wave heating and CD

Using TRANSP to test q_0 and β_N control via beam power and outer gap size actuation

- Boundary can have strong effect on q profile through
  - Effect on **beam deposition** profile
  - Effect on **bootstrap current** through change in elongation

- Two **reference boundaries** with different outer gap sizes were chosen, and **interpolated between** based on the feedback controller request



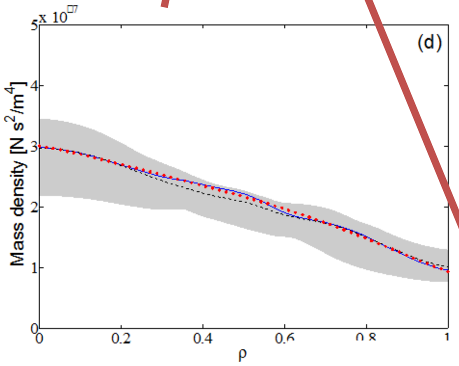
M.D. Boyer, NF 2015

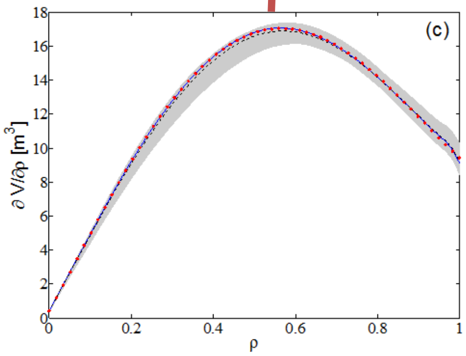
Simplified model used for rotation profile control design in NSTX-U

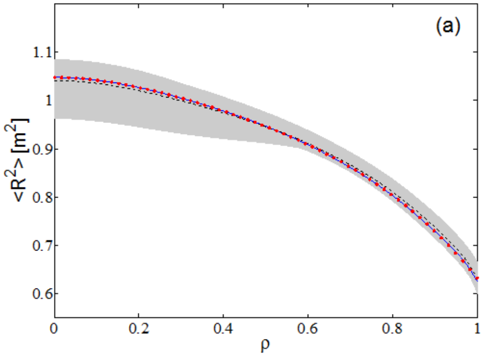
- Using simplified form of toroidal momentum equation for design, profiles derived from TRANSP

Rotation

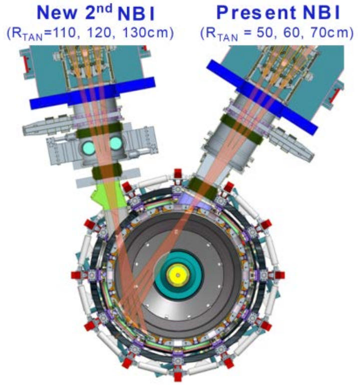
$$\sum_i n_i m_i \langle R^2\rangle \frac{\partial\omega}{\partial t} = \left(\frac{\partial V}{\partial\rho}\right)^{-1}\frac{\partial}{\partial\rho}\left[\frac{\partial V}{\partial\rho}\sum_i n_i m_i \chi_\phi \langle R^2(\nabla\rho)^2\rangle\frac{\partial\omega}{\partial\rho}\right] + T_{NBI} + T_{NTV}$$



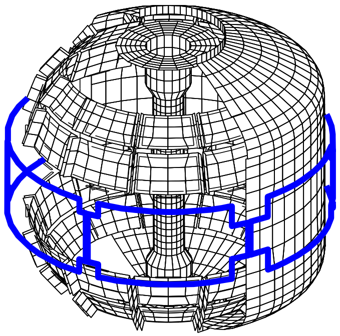




New NBI
(central torque)

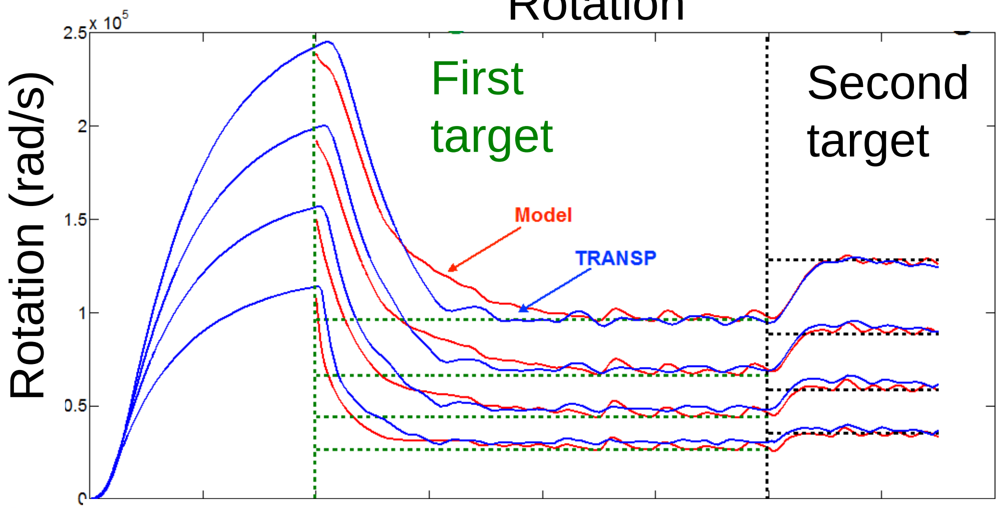


3D Field Coil
(edge torque)

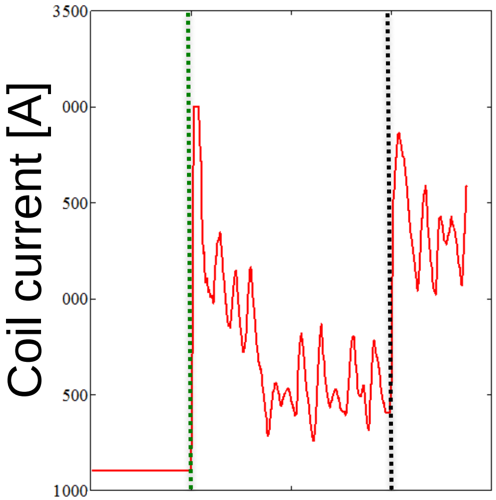


State-space controller achieves good tracking in TRANSP simulations

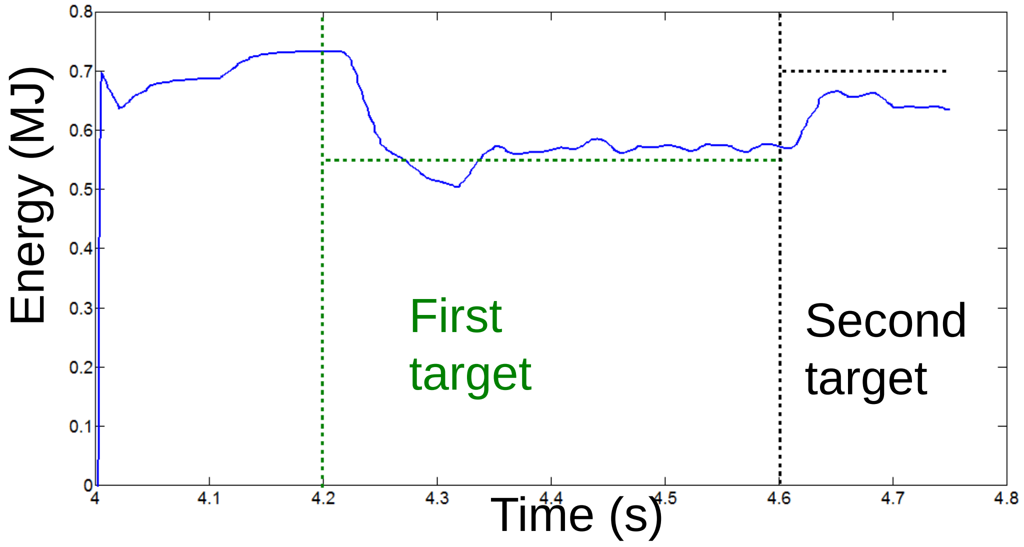
Rotation



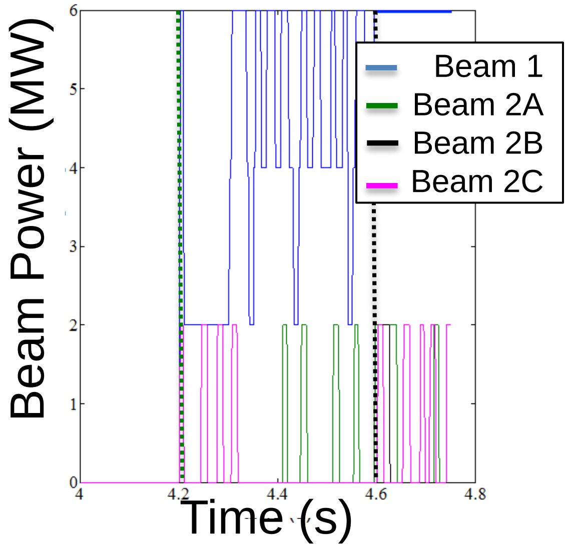
Coil current



Stored energy



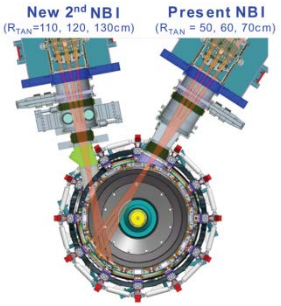
Beam power

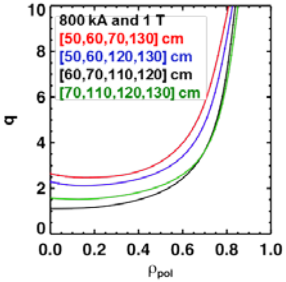


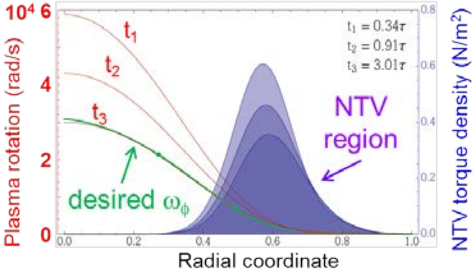
Advanced Scenarios and Control Research Plans for FY2016-18:

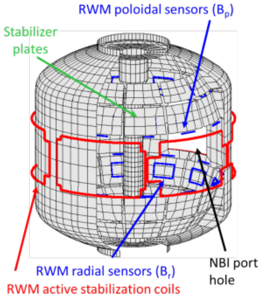
Implement advanced controls, explore high non-inductive & I_P scenarios

- **FY16**: Re-establish NSTX-U control and plasma scenarios R16-3
  - Vertical/shape control, NBI beta feedback control, EF/RWM control
    - Assess new 2nd NBI current-drive vs. R_{TAN}, n_e, outer gap
      - Push toward 100% non-inductive at higher B_T, P_{NBI}
      - Quantify impact of broadened J(r), p(r) on confinement, stability
    - Explore scenarios (τ_E, l_i, MHD) at up to 60% higher I_P, B_T
- **FY17**: Explore scenarios at full I_P and B_T capability of NSTX-U
  - Goal: Access 100% non-inductive, test small I_P overdrive R17-4
- **FY18**: Control of current and rotation profiles to improve global stability limits and extend high performance operation R18-2



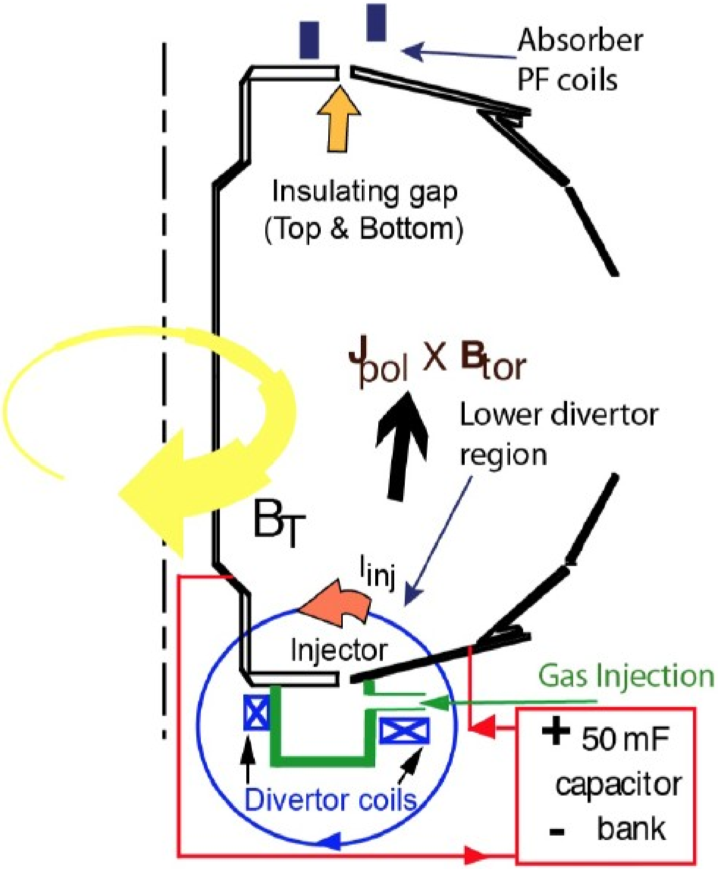






ST-FNSF may need solenoidless current start-up method
Coaxial Helicity Injection (CHI) effective for current initiation

CHI developed on HIT, HIT-II
Transferred to NSTX / NSTX-U



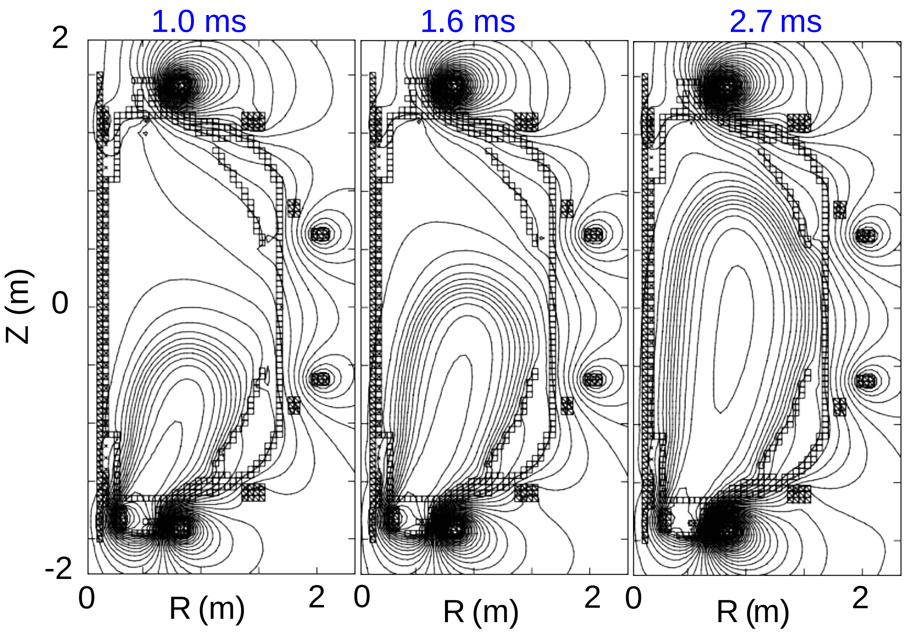
R. Raman et al., PRL 2006

UNIVERSITY of WASHINGTON

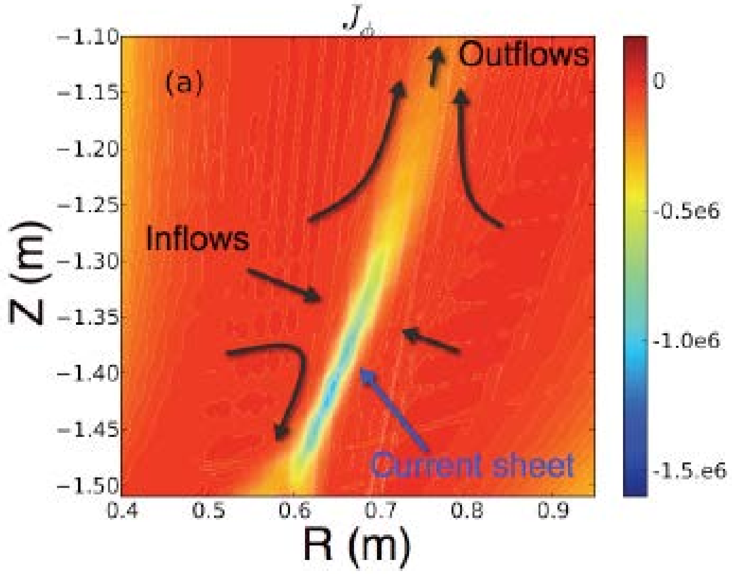
NSTX: 150-200kA closed flux current

NSTX-U: CHI projects to 300-400kA

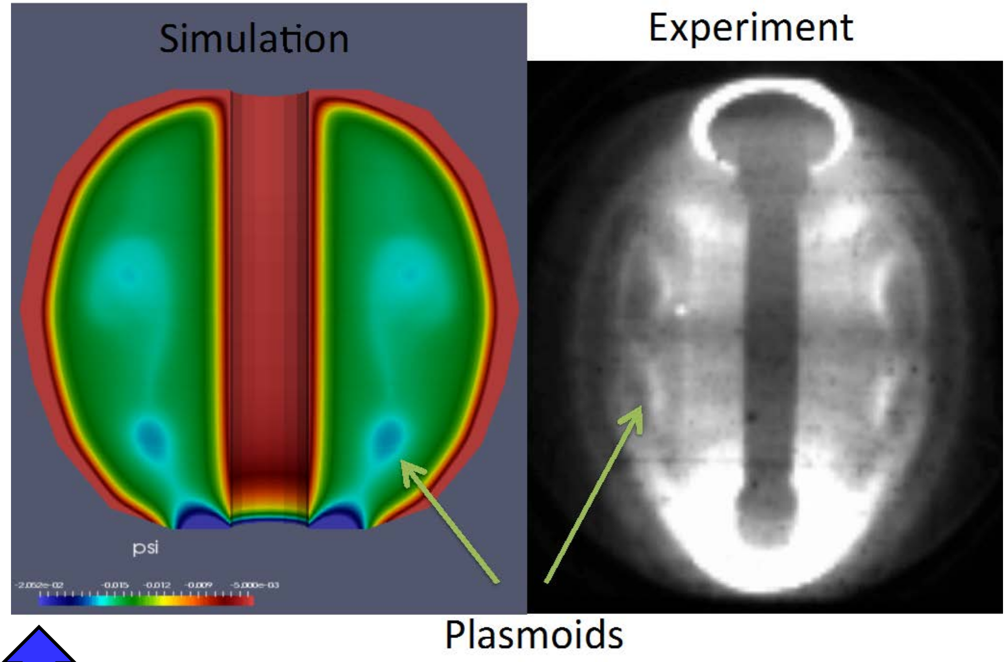
TSC axisymmetric simulation of CHI startup

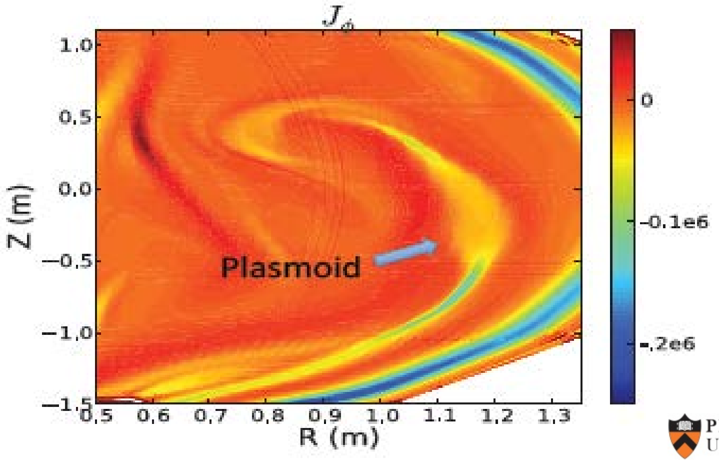


At high Lundquist number, plasmoid-mediated reconnection identified as assisting in flux closure



- **Sweet Parker (S-P) reconnection in the injector region at low Lundquist number**





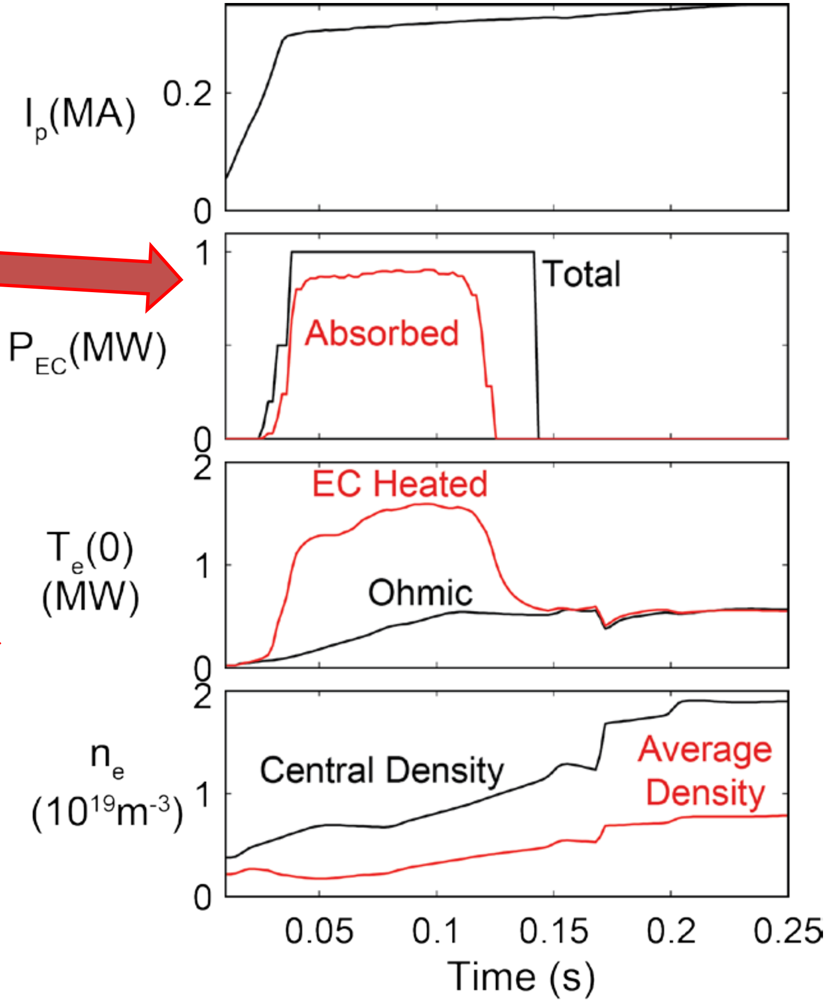
- Plasmoids seen in NSTX CHI
- Plasmoids potentially important for extrapolating CHI to FNSF

NIMROD Simulations F. Ebrahimi, et al., PRL (2015)

TRANSP simulations predict that 28 GHz ECH very effective at heating NSTX-U start-up plasmas

- TRANSP time-dependent simulations with 1 MW of 28 GHz O-mode ECH predict a rapid increase in first-pass absorption from 5% to 75% as $T_e(0)$ increases from 10 eV to 1 keV in ~10 ms

- **Issue:** ECH can be used for ~150 ms before the plasma $n_e > n_{cutoff}$



Experiments: Get new density information from CHI and low-I_P RF target plasmas

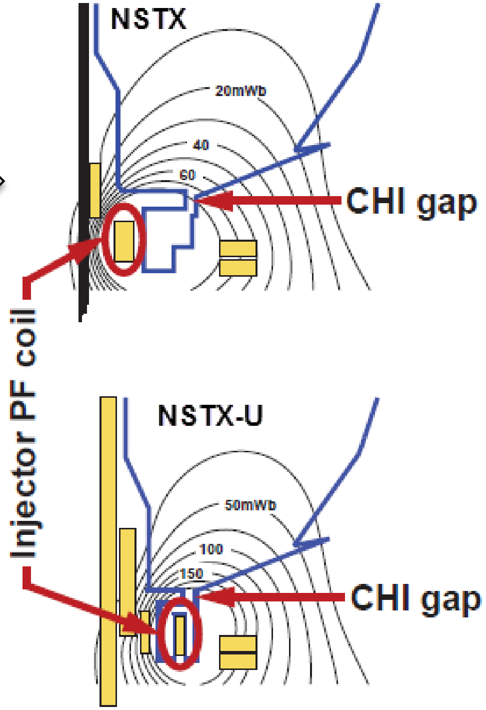
Modeling: Assess EC heating against plasma parameter variations

Solenoid-Free Start-up and Ramp-up Research Plans for FY2016-18:

Prepare CHI for NSTX-U, assess CHI/NBI start-up/ramp-up

- FY16-17: Establish NSTX-U CHI, assess impact of new injector, gap, higher B_T
- FY16-17: Initial tests of small NBI+BS overdrive ramp-up using new 2nd NBI and higher B_T
- FY18: Assess transient CHI current start-up potential in NSTX-U
  - Characterize maximum start-up current vs. injector flux, CHI voltage, toroidal field, high-power ECH (if available – incremental)
  - Study reconnection region and plasmoid instabilities with improved cameras/imaging

R18-3

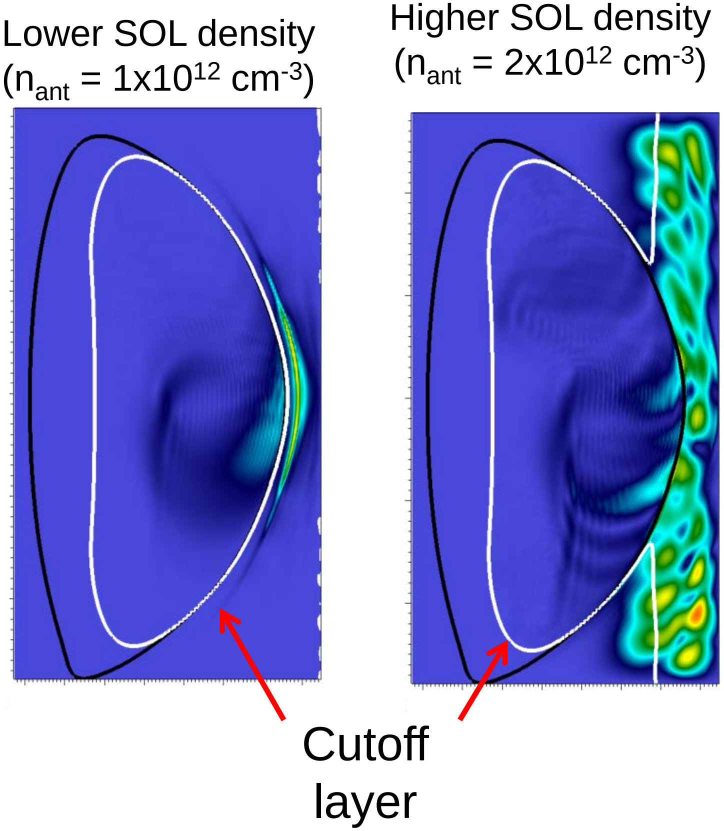


Wave Physics Research Plans for FY2016-18:

Simulate, develop reliable FW-heated H-mode, assess impurity control

- FY16: First data on HHFW heating efficiency at higher B_T
- FY17: Incremental: Assess fast-wave SOL losses and core thermal and fast-ion interactions at increased B_T, I_P IR17-1
- FY18: Assess HHFW as means of core impurity expulsion as well as a potential source of edge impurities R18-1

$k_\varphi = 13\ m^{-1}$
Heating phasing



AORSA simulations

N. Bertelli, NF 2015, 2016

Outline

- NSTX highlight overview, NSTX-U run progress
- NSTX-U mission, priorities, FY16-18 overview
- FY16-18 research plans
- Milestone summary
- ITPA contributions
- ST-FNSF / Pilot Plant study highlights
- Summary

Administration FY2017 request-level provides run-time and full field + current to exploit new Upgrade capabilities

	FY2016	FY2017	FY2018
Run Weeks:	18	16	12
Boundary Science + Particle Control	R16-1 Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	R17-1 Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density R17-2 Assess high-Z divertor PFC performance and impact on operating scenarios	R18-1 Assess impurity sources and edge and core impurity transport
Core Science	R16-2 Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile	R17-3 Assess τ_E and local transport and turbulence at low ν^* with full confinement and diagnostic capabilities	
Integrated Scenarios	R16-3 Develop physics + operational tools for high-performance: κ, δ, β, EF/RWM	R17-4 Develop high-non-inductive fraction NBI H-modes for sustainment and ramp-up	R18-2 Control of current and rotation profiles to improve global stability limits and extend high performance operation R18-3 Assess transient CHI current start-up potential in NSTX-U
FES 3 Facility Joint Research Target (JRT)	C-Mod leads JRT Assess disruption mitigation, initial tests of real-time warning, prediction	DIII-D leads JRT Examine effect of configuration on operating space for dissipative divertors	NSTX-U leads JRT TBD

← Begin ~1 year outage for divertor cryo-pump

Incremental accelerates transport, divertor, and RF research, strongly utilizes facility, supports high-priority enhancements

	FY2016	FY2017	FY2018
Run Weeks: Incremental	18	16 18	12 16
Boundary Science + Particle Control	R16-1 Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	R17-1 Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density R17-2 Assess high-Z divertor PFC performance and impact on operating scenarios	R18-1 Assess impurity sources and edge and core impurity transport IR18-1 Investigation of power and momentum balance for high density and impurity fraction divertor operation
Core Science	R16-2 Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile	R17-3 Assess τ_E and local transport and turbulence at low ν^* with full confinement and diagnostic capabilities	IR18-2 Assess role of fast-ion driven instabilities versus micro-turbulence in plasma thermal energy transport Begin ~1 year outage for divertor cryo-pump
Integrated Scenarios	R16-3 Develop physics + operational tools for high-performance: κ, δ, β, EF/RWM	IR17-1 Assess fast-wave SOL losses, core thermal and fast ion interactions at increased field and current R17-4 Develop high-non-inductive fraction NBI H-modes for sustainment and ramp-up	R18-2 Control of current and rotation profiles to improve global stability limits and extend high performance operation R18-3 Assess transient CHI current start-up potential in NSTX-U
FES 3 Facility Joint Research Target (JRT)	C-Mod leads JRT Assess disruption mitigation, initial tests of real-time warning, prediction	DIII-D leads JRT Examine effect of configuration on operating space for dissipative divertors	NSTX-U leads JRT TBD

Outline

- NSTX highlight overview, NSTX-U run progress
- NSTX-U mission, priorities, FY16-18 overview
- FY16-18 research plans
- Milestone summary
- ITPA contributions
- ST-FNSF / Pilot Plant study highlights
- Summary

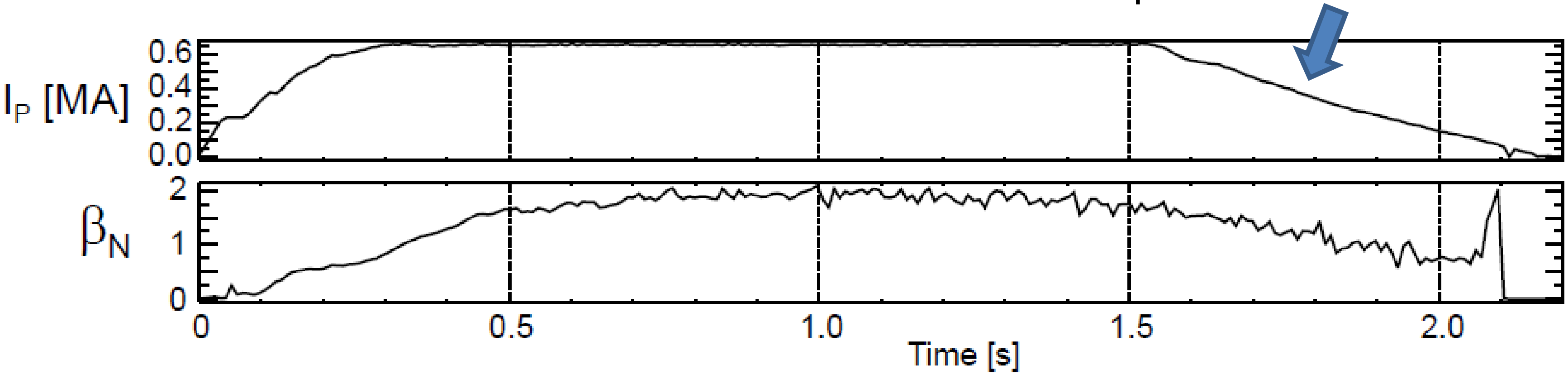
Supporting ITER through ITPA participation

- Active in 31 JEX/JACs with reps in every Task Group, leadership in several

	Integrated Operating Scenarios
IOS-1.2	Divertor heat flux reduction in ITER baseline scenario (considering)
IOS-1.3	Operation near P_{LH} (considering)
IOS-2.1	Compare helium H-modes in different devices (considering)
IOS-3.3	Core confinement for q(0)=2 (considering)
IOS-5.2	Maintaining ICRH coupling in expected ITER regime
	Boundary Physics
PEP-26	Critical edge parameters for achieving L-H transition
PEP-28	Physics of H-mode access with different X-point height (considering)
PEP-29	Vertical jolts/kicks for ELM triggering and control
PEP-30	ELM control by pellet pacing in ITER-like conditions and consequences for plasma confinement
PEP-31	Pedestal structure and edge relaxation mechanisms in I-mode (considering)
PEP-37	Effect of low-Z impurity on pedestal and global confinement
DSOL-31	Leading edge power loading and monoblock shaping
DSOL-34	Far-SOL fluxes and link to detachment (considering)
DSOL-35	In-out divertor ELM energy density asymmetries (consdiering)
	Energetic Particles
EP-6	Fast ion losses and associated heat loads from edge perturbations (ELMs and RMPs)

	Macroscopic Stability
MDC-1	Disruption mitigation by massive gas jets
MDC-8	Current drive prevention/stabilization of NTMs (considering)
MDC-15	Disruption database development
MDC-17	Active disruption avoidance
MDC-18	Evaluation of axisymmetric control aspects
MDC-19	Error field control at low plasma rotation
MDC-21	Global mode stabilization physics and control
MDC-22	Disruption prediction for ITER
	Transport and Turbulence
TC-9	Scaling of intrinsic plasma rotation with no external momentum input (considering)
TC-10	Experimental identification of ITG, TEM and ETG turbulence and comparison with codes
TC-11	He and impurity profiles and transport coefficients
TC-14	RF rotation drive (considering)
TC-15	Dependence of momentum and particle pinch on collisionality
TC-17	ρ^* scaling of intrinsic torque (considering)
TC-19	Characteristics of I-mode plasmas (considering)
TC-24	Impact of resonant magnetic perturbations on transport and confinement (considering)

- New: NSTX-U can / will contribute to IOS controlled ramp-down studies for ITER



Recent design studies show ST potentially attractive as Fusion Nuclear Science Facility (FNSF) and Pilot Plant

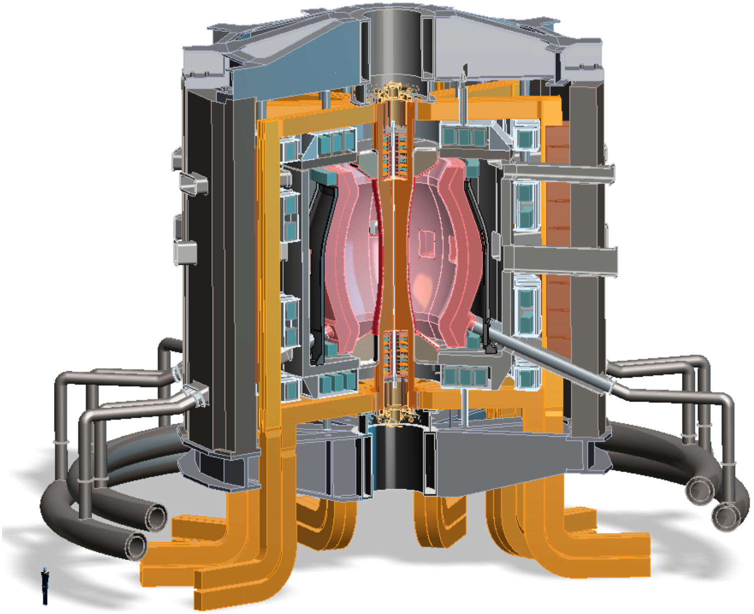
FNSF: Provide neutron fluence for material/component R&D (+ T self-sufficiency?)

Pilot Plant: Electrical self-sufficiency: $Q_{eng} = P_{elec} / P_{consumed} \geq 1$ (+ FNSF mission?)

FNSF with copper TF coils

$A=1.7$, $R_0 = 1.7m$, $\kappa_x = 2.7$, $B_T=3T$

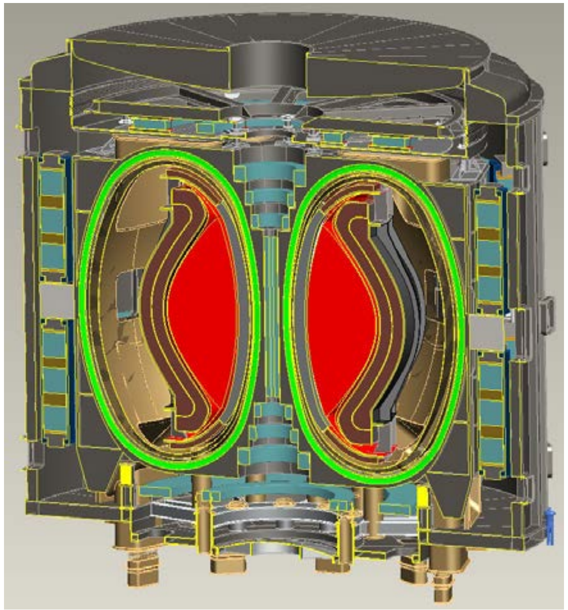
Fluence = $6MWy/m^2$, TBR ~ 1



FNSF / Pilot Plant with HTS TF coils

$A=2$, $R_0 = 3m$, $\kappa_x = 2.5$, $B_T = 4T$

$6MWy/m^2$, TBR ~ 1, Q_{eng} ~ 1



Designs integrate ST higher κ , β_N and advanced divertors (+ HTS TF for Pilot Plant)

Paper submitted to Nuclear Fusion

Outline

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NSTX-U research program well aligned with FESAC / FES / Community Workshop strategic priorities

	NSTX-U contributions:
• Plasma material interactions	
– Scrape off layer / divertor physics	◀Low-A, advanced divertors
– PMI and long pulse divertor simulators	◀MAPP + surface science
– Engineering innovations for plasma exhaust	◀Liquid metal PFCs
– Plasma core-edge integration	◀Long-term NSTX-U goal
• Transients	
– Disruption prediction, avoidance, mitigation	◀Kinetic MHD, PCS, MGI
– ELM suppression with RMP	◀NCC RMP (incremental)
– Naturally ELM-free operation	◀Li-wall scenarios, EPH
– ELM pacing	◀Granule injector, 3D fields
• Integrated Simulations	
– Disruption prevention, avoidance, mitigation	◀Kinetic MHD codes
– Plasma boundary (Ped, SOL, PMI)	◀XGC, UEDGE, Walldyn, …
– Whole device modeling	◀TRANSP, control models
• Plasma science frontiers	◀EM turbulence, plasmoids
• Establishing physics basis for FNSF	◀Entire NSTX-U Program

Summary: NSTX-U FY2016-18 research plan strongly supports FES 10 year vision, scientific organization

- **Burning Plasma Science: Foundations**
  - Expect transport, stability discoveries in new high-β + low-ν* regime
  - Core: Non-linear AE* / fast-ion dynamics, disruptions, response to 3D δB
  - Boundary: SOL-widths & turbulence, advanced divertors, Li-based PFCs
- **Burning Plasma Science: Long-Pulse**
  - PMI: EAST collaboration: long-pulse performance of high-Z, liquid metals
  - FNSF: NSTX-U provides critical data on confinement, stability, sustainment
- **Burning Plasma Science: High-Power**
  - Robust Control: Goal: high-β + full non-inductive, disruption avoidance
- **Discovery Plasma Science**
  - Measurement Innovation: B / δB: MSE-LIF / CPS, PSI / SOL: MAPP / MLP

➢ Incremental funding needed to fully utilize NSTX-U facility and implement high-priority enhancements

➢ -5% in FY18 → 7 FTE reduction, delay divertor cryo-pump 0.5-1 year

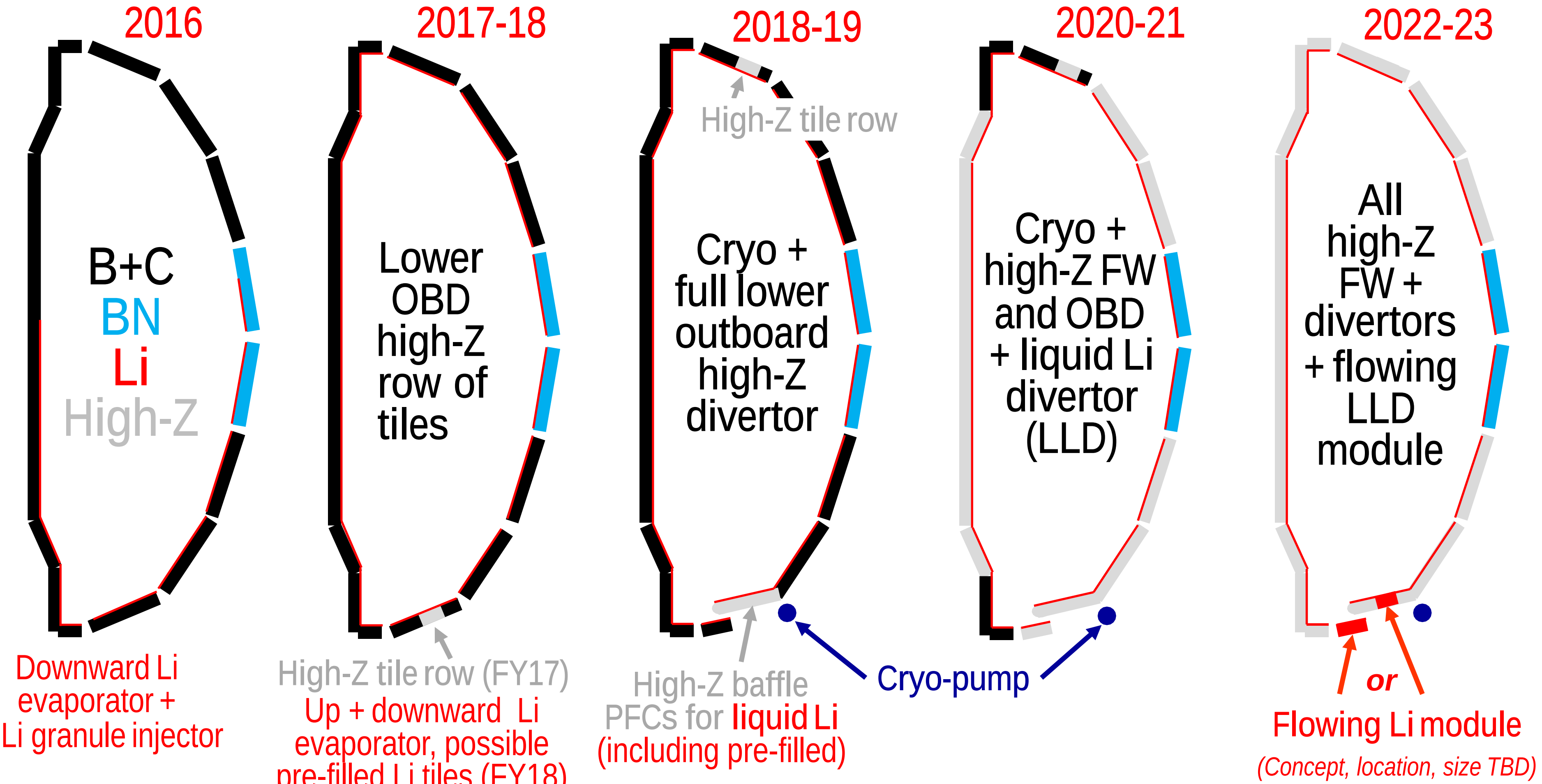
Backup Slides

Summary of FY2016-18 NSTX-U Research Milestones

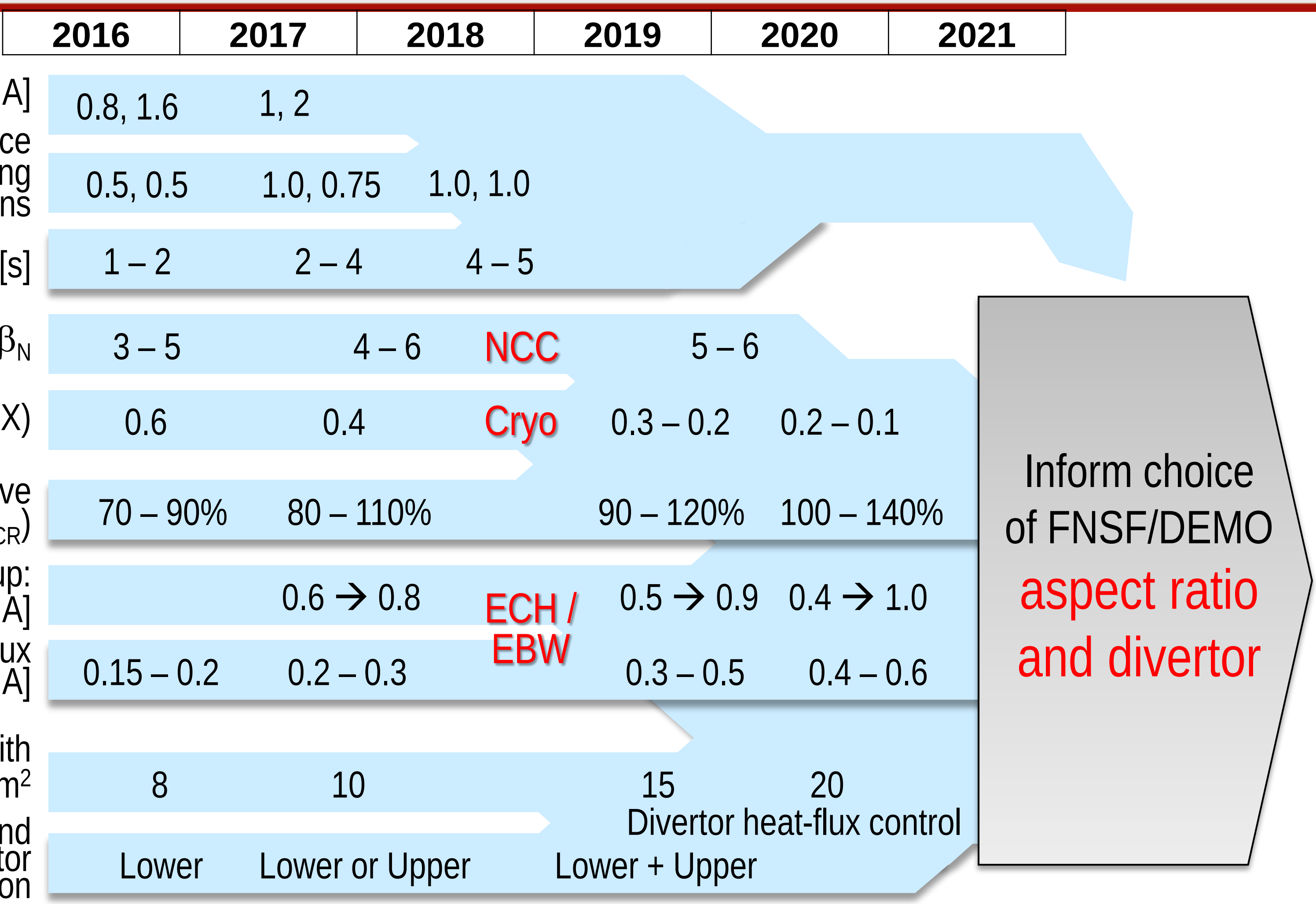
- **FY2016**
  - Obtain 1st data at 60% higher field/current, 2-3× longer pulse: — Milestone #
    - Re-establish sustained low l_i / high-κ operation above no-wall limit — **R16-3**
    - Study thermal confinement, pedestal structure, SOL widths — **R16-1**
    - Assess current-drive, fast-ion instabilities from new 2nd NBI — **R16-2**
- **FY2017**
  - Extend NSTX-U performance to full field, current (1T, 2MA)
    - Assess divertor heat flux mitigation, confinement at full parameters — **R17-1,3**
  - Access full non-inductive, small current over-drive — **R17-4**
  - First 2D high-k scattering, test prototype high-Z tiles, HHFW — **R17-2** **IR17-1**
- **FY2018**
  - Study low-Z and high-Z impurity transport — **R18-1**
  - Assess causes of core electron thermal transport — **IR18-2**
  - Test advanced q profile and rotation profile control — **R18-2**
  - Assess CHI plasma current start-up performance — **R18-3**
  - Divertor power and momentum balance (vapor shielding) — **IR18-1**

NSTX-U boundary / PFC plan: add divertor cryo-pump, transition to high-Z wall, study flowing liquid metal PFCs

- **5yr goal: Integrate high τ_E and β_T with 100% non-inductive**
- **10yr goal: Assess compatibility with high-Z and liquid lithium PFCs**



NSTX-U 5 year plan: Develop physics/scenario understanding needed to assess ST viability as FNSF/DEMO, support ITER



	2016	2017	2018	2019	2020	2021
Max B_T [T], I_P [MA]	0.8, 1.6	1, 2				
Structural force and coil heating limit fractions	0.5, 0.5	1.0, 0.75	1.0, 1.0			
Nominal τ_{pulse} [s]	1 – 2	2 – 4	4 – 5			
Sustained β_N	3 – 5		4 – 6 NCC		5 – 6	
ν^* / ν^* (NSTX)	0.6	0.4	Cryo	0.3 – 0.2	0.2 – 0.1	
Non-inductive fraction ($\Delta t \geq \tau_{CR}$)	70 – 90%	80 – 110%		90 – 120%	100 – 140%	
NBI+BS I_P ramp-up: initial → final [MA]		0.6 → 0.8	ECH / EBW	0.5 → 0.9	0.4 → 1.0	
CHI closed-flux current [MA]	0.15 – 0.2	0.2 – 0.3		0.3 – 0.5	0.4 – 0.6	
P_{heat} [MW] with q_{peak} < 10MW/m^2	8	10		15	20	
				Divertor heat-flux control		
Snowflake and radiative divertor exhaust location	Lower	Lower or Upper		Lower + Upper		

Inform choice of FNSF/DEMO **aspect ratio and divertor**

Cryo: access lowest ν^*, compare to Li **ECH / EBW**: bridge T_e gap from start-up to ramp-up

Off-midplane non-axisymmetric control coils **(NCC)**: rotation profile control (NTV), sustain high β_N

NSTX-U Science organizational structure for 2015-2016:
3 Science Groups, 9 Topical Science Groups, 1 Task Force

Science Group (SG)

Topical Science Group (TSG)

Task Force (TF)

Working Group (WG)

12 collaborating institutions engaged in NSTX-U science program leadership →

Collaborators in Science Program Leadership:

1	ORNL
2	University of Wisconsin
3	LLNL
4	UT Knoxville
5	University of Illinois
6	Columbia University
7	Princeton University
8	Johns Hopkins University
9	UC Irvine
10	UC Los Angeles
11	University of Washington
12	MIT

Boundary Science Group
R. Maingi, C.-S. Chang (deputy)

Pedestal Structure and Control
A. Diallo, R. Maingi
Theory/Modelling: J. Canik[1]
University Rep: D. Smith[2]

Divertor and Scrape-Off-Layer
V. Soukhanovskii[3], J.-W. Ahn[1]
Theory/Modelling: D. Stotler
University Rep: O. Schmitz[2]

Materials and PFCs
M. Jaworski, C. Skinner
Theory/Modelling: B. Wirth[4]
University Rep: J.-P. Allain[5]

Core Science Group
S. Kaye, S. Sabbagh[6] (deputy)

Macroscopic Stability
J. Berkery[6], J.-K. Park
Theory/Modelling: N. Ferraro
University Rep: D. Brennan[7]

Transport and Turbulence
W. Guttenfelder, Y. Ren
Theory/Modelling: W. Wang
University Rep: K. Tritz[8]

Energetic Particles
M. Podestá, D. Liu[9]
Theory/Modelling: N. Gorelenkov
University Rep: N. Crocker[10]

Integrated Scenarios Group
S. Gerhardt, R. Raman[11] (deputy)

Advanced Scenarios and Control
D. Battaglia, S. Gerhardt
Theory/Modelling: F. Poli
University Rep: E. Kolemen[7]

Solenoid-free Start-up & Ramp-up
D. Mueller, R. Raman[11]
Theory/Modelling: F. Ebrahimi[7]

Wave Heating and Current Drive
R. Perkins, J. Hosea
Theory/Modelling: N. Bertelli
University Rep: P. Bonoli[12]

Particle Control Task Force (FY2016-17)
Leader: J. Canik[1], Deputy: R. Maingi

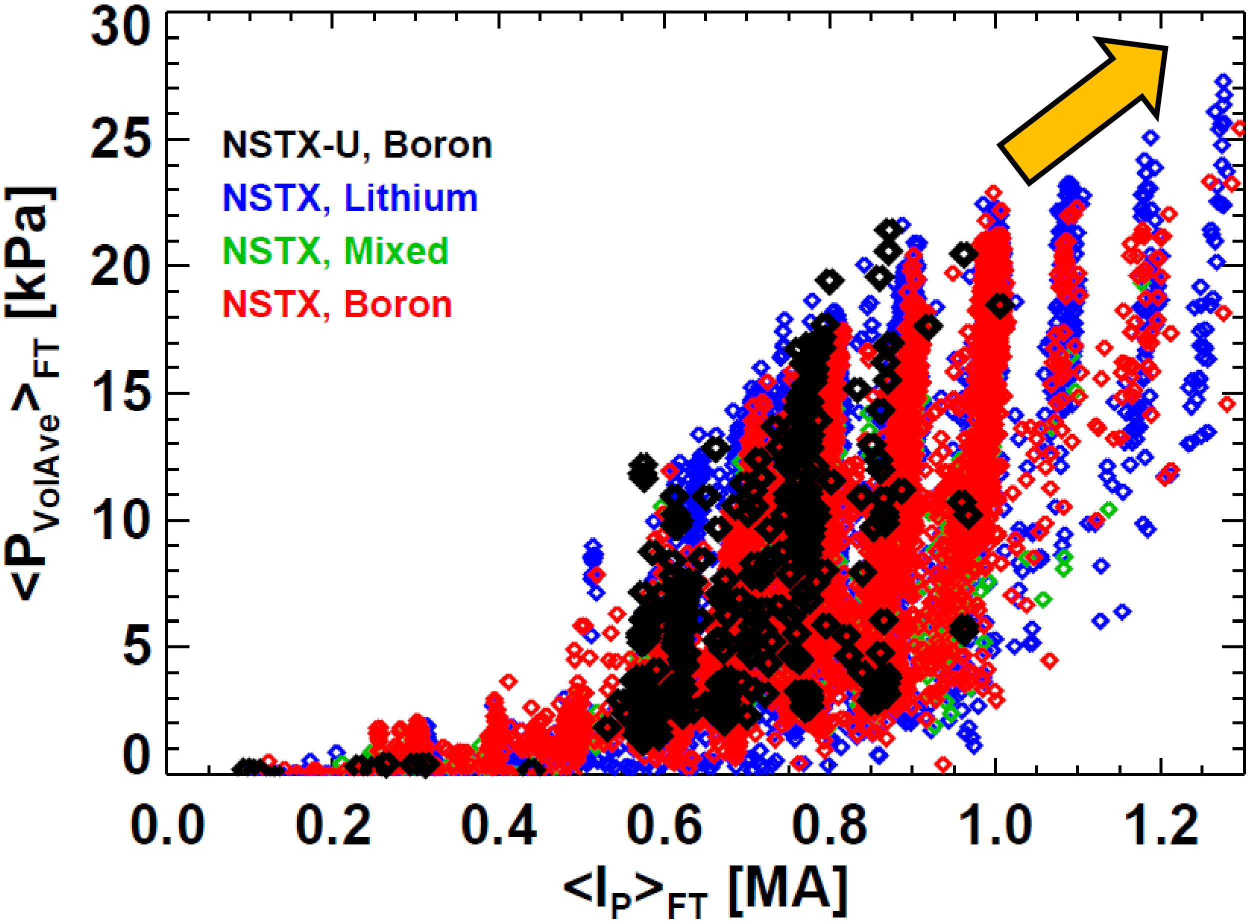
Goal: Develop pumping and fueling tools, operating scenarios, and control systems to achieve main-ion and impurity density control for long-pulse

Disruption Prediction, Avoidance, and Mitigation (DPAM) Working Group
Leader: S. Sabbagh[6], Deputy: R. Raman[11]

Goal: Improve understanding of prediction, avoidance, and mitigation of disruptions in tokamaks, achieve acceptable levels of disruption frequency and severity

Each TSG has a leader, deputy, theory rep, and at least 1 university rep to enhance university participation

NSTX-U has matched NSTX highest flat-top pressures for plasma currents up to 0.9MA

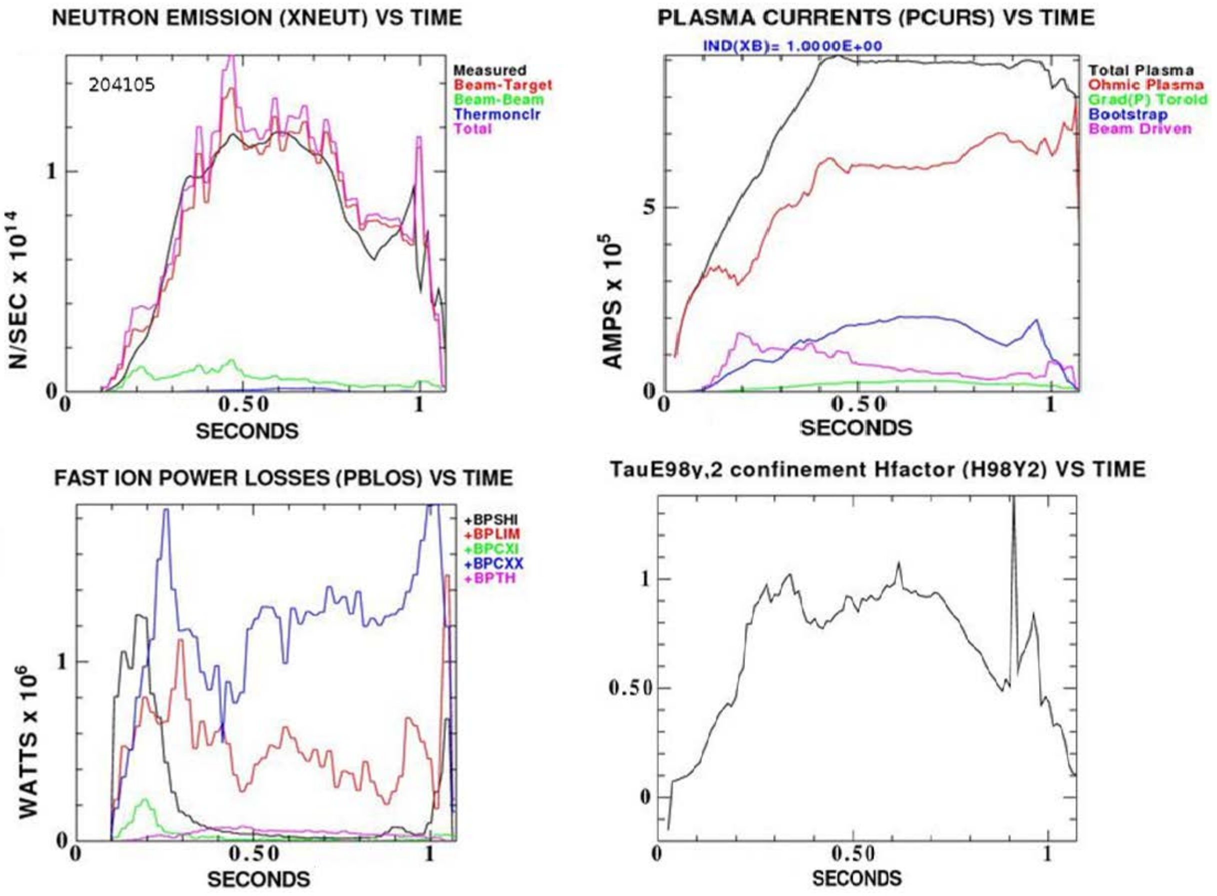


- **Near-term: I_P → 1.1 – 1.3MA**
  - – **Support core, pedestal, SOL scaling XPs, access higher W_{tot}, ⟨p⟩**

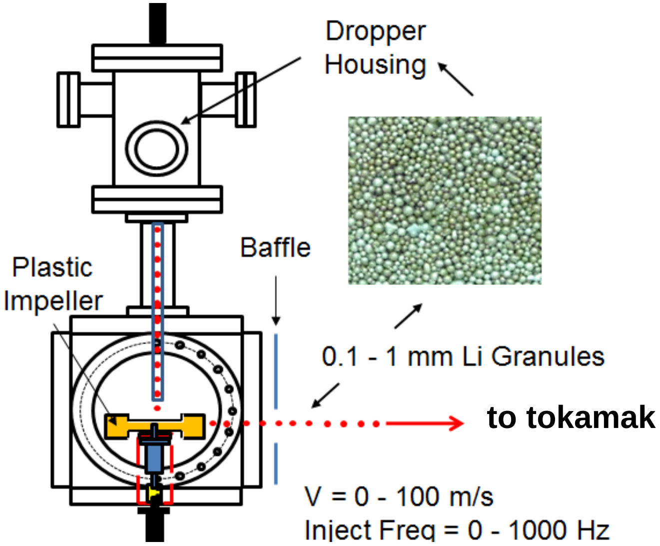
New NSTX-U tool: Between and Among Shot TRANSP (BEAST) will aid experiment execution

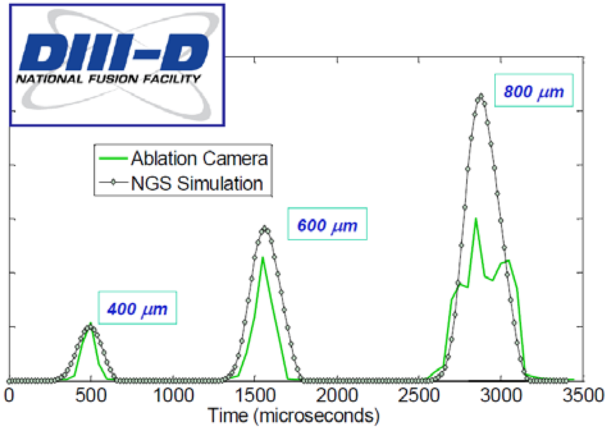
- Typical BEAST run completed in 8 mins
  - NSTX-U has 15-20 mins between shots
- In preparation for next shot, session leader can gauge:
  - Non-inductive fraction
  - Beam loss
  - Confinement quality
  - Any TRANSP quantity…

NSTX-U BEAST TRANSP run (no CHERS)



Impurity Granule Injector (IGI) will be used on NSTX-U for pedestal / ELM control and scenario optimization





The ablation intensity is plotted vs time, NGS field parameters (η, f_B, f_L) are set to match calculated ablation time with measurements for a typical 800 micron granule. Peak ablation intensity and NGS rate are normalized for the smallest granule size.

- Successful EAST and DIII-D demonstrations / collaborations
  - – Capable of up to 0.5 kHz injection
- IGI will be tested on NSTX-U for high-frequency ELM pacing
  - – Possible density control technique:
    - Combine Li coatings for D pumping with LGI for ELM-expulsion of carbon
  - – Goal: reduce Z_{eff} to ~2-2.5
  - – Injection of Li granules could also potentially replenish PFC Li coatings
- Using Neutral Gas Shielding (NGS) model to interpret granule ablation and penetration depth vs. mass

NSTX-U / STs will improve understanding of RMP ELM mitigation / suppression physics

- ELMs in STs and tokamaks respond to applied 3D fields in different ways
  - RMP ELM suppression not achieved in STs (yet)
    - 3D fields triggered ELMs in NSTX
  - Understanding such differences could greatly improve confidence in scaling RMP ELM mitigation to ITER

- NSTX-U (with MAST-U) offer a unique capability to validate ELM suppression models across the ST and tokamak regimes

- Modeling goal: Combine models of 3D perturbed equilibrium (M3D-C1) and transport (XGC) to yield a quantitative, predictive model for transport in 3D fields

- M3D-C1 is being used to predict and optimize plasma response to NCC coils in NSTX-U